proj: **XENON TPC**
Xenon Pressure Chamber
title: **Pressure Safety Note**

DRAFT, for review

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1. Introduction

This Safety Note covers a pressure vessel and associated inert gas system for a physics research experiment involving neutrinoless double beta decay, using Xenon gas. The heart of the system is a pressure vessel recently acquired by LBNL from LLNL. There are new components both purchased, and LBNL designed (in accordance with ASME Boiler and Pressure Vessel Code Section VIII, Div. 1, 2007), which will be attached to this pressure vessel, which are treated in this note. This Safety Note is to assure that the Experiment meets LBNL Pressure Safety requirements of PUB-3000. Under PUB3000, sec 7.6.1, it is classified as a High Hazard Pressure System, since there are gas pressures above 150 psig. An AHD is not required for the Xenon or Argon gases, nor any of the other materials inside, but there may be pressure and process hazards, so an AHD will be formulated.

The pressure vessel will enclose a small detector called a Time Projection Chamber (TPC) with Xenon gas used as both the electron drift volume and for electrical insulation. The vessel was designed by LLNL, and used at LLNL from 2000-2009 for a similar purpose, and has not been modified from the original design. LLNL Mechanical Engineering Safety Note MESN99-020-OA (1999) contains the vessel design calculations, performed in accordance with ASME Boiler and Pressure Vessel Code Section VIII (1995), and is included here in the Appendix. It includes pressure testing procedures. Also included is a copy of the original pressure test at LLNL for the vessel and head. The attached components consist of a 2" diameter high vacuum/high pressure valve, a Kimball physics octagonal vacuum chamber, a spool connecting the octagon to the vessel lid, assorted cabling feedthroughs, and a gas handling system composed of small diameter high pressure metal tubing, purifiers, valves, and pumps. The gas system includes a cryogenic Xenon reclamation cylinder, which was designed, built, and tested by Acme Cryogenics for LLNL, for 3000 psi MOP. We will be using it here at LBNL up to a pressure of 950 psi MOP. Its design calculations and test report are also included in the Appendix (LLNL M.E. Safety Note MESN99-038-OA). The pressure vessel is shown below:

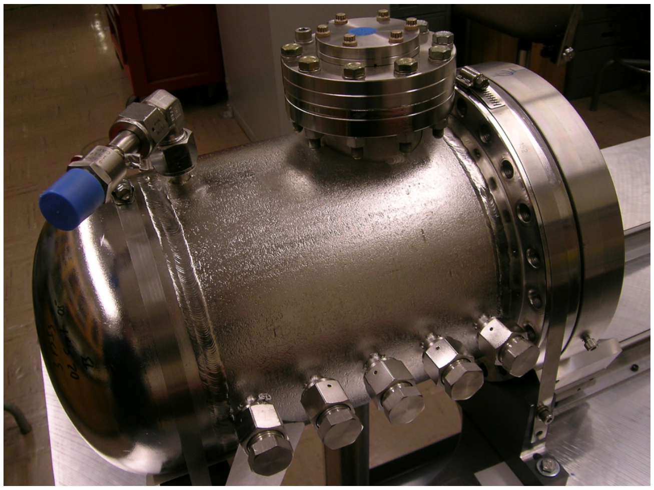


Fig. 1 Main pressure Vessel, 850 psig MOP

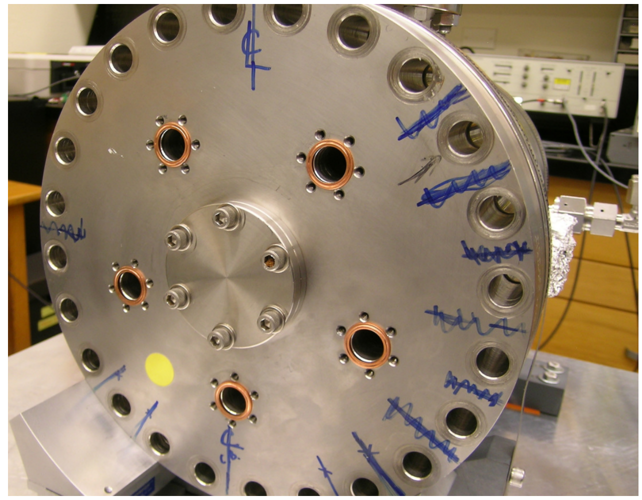


Fig. 2 Flat Heat for 350 psig MOP (CF seals)

Pressures for use at LBNL

Maximum Operating Pressure   Maximum Allowable Working Pressure

$P_{MOP} := 300psi$ $P_{MAWP} := 350psi$

Initial Maximum Operating and Allowable Working Pressures

$P_{MOP\_i} := 225psi$ $P_{MAWP\_i} := 250psi$

(to be used initially with existing Ceramtec SHV-20 connectors (see below) until higher rated feedthroughs are obtained)

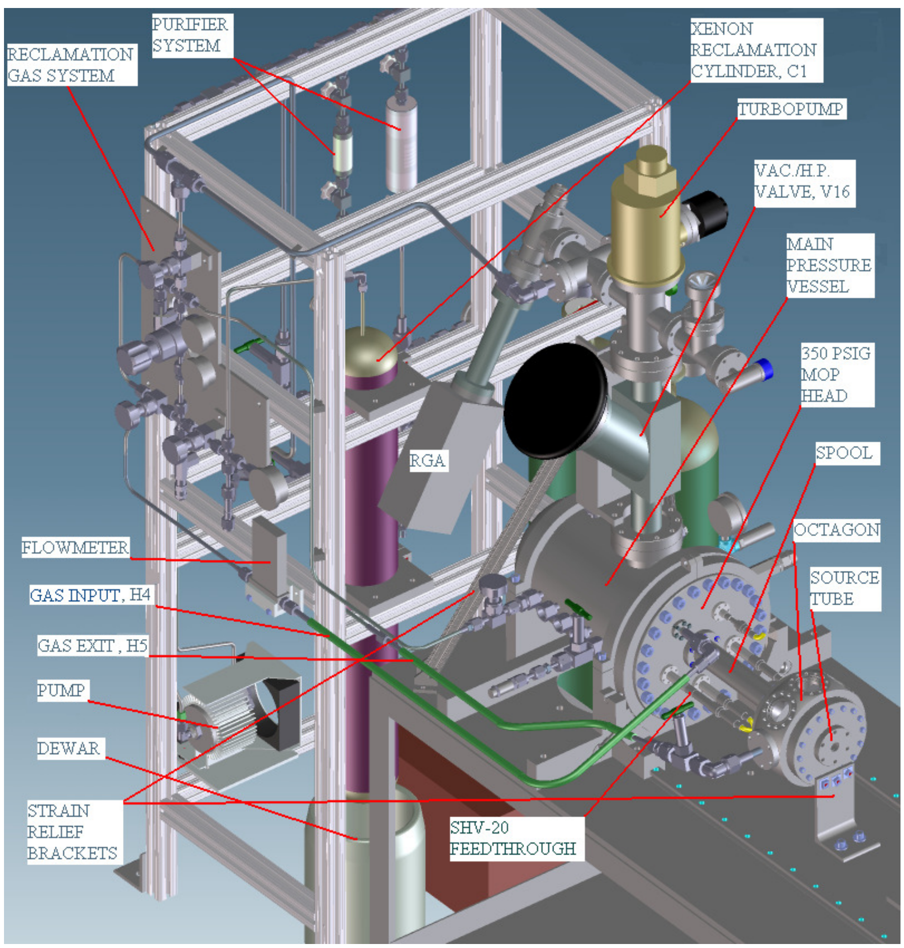


Fig. 3 LBNL configuration: pressure vessel with cabling extension spool, octagon vac. cham. & gas sys.

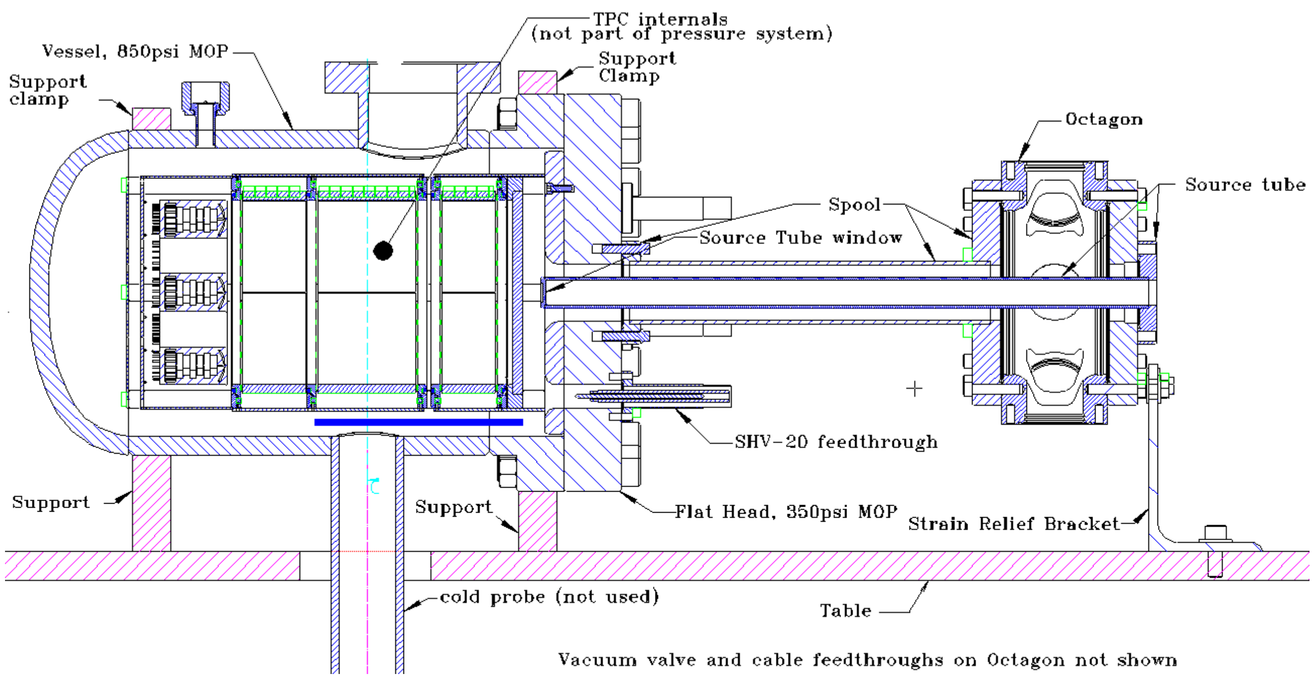


Fig. 4, Cross Section, longitudinal-vertical

2. System Description and Basic Operation

The main pressure vessel is approximately 8 inches in diameter and 14 inches long, (inside volume), and fabricated from 316L and 304 stainless steel. It will be operated at LBNL at a 300 psig maximum operating pressure (MOP), with a maximum allowable pressure (MAWP) of 350 psig. Minimum pressure is high vacuum. The main vessel was designed for operation up to 850 psig MOP, with a section of the chamber operated at LN2 temperature. There are two flat heads for it, only one of which will be used at LBNL, this head has an MAWP of 406 psig. At LBNL, the chamber will be used with inert gases only, mainly Xenon and Argon, as well as high vacuum. It will be operated only in temperature range of room temperature to 50C; the cryogenic section will not be used, and it will be labeled as such to prohibit use. An associated gas system is used to supply gas to the chamber, to pressurize and depressurize the vessel, and to circulate Xenon continuously through the detector, primarily to purify the Xenon gas to a high purity state, but also to eliminate any thermal convection currents from electronics inside the vessel. Argon may be used for initial flushing of air, H20, etc. when the vessel is first assembled, and perhaps for leak checking under pressure. A 5.4L stainless steel Xenon reclamation cylinder is used to condense/ freeze out Xenon in order to open up the vessel without venting the Xenon. It will be left open during some operations, and so is considered part of the vessel volume. The total system stored energy is 54 kJ for either of these monatomic gasses @MAWP = 350 psig. A schematic is shown below:

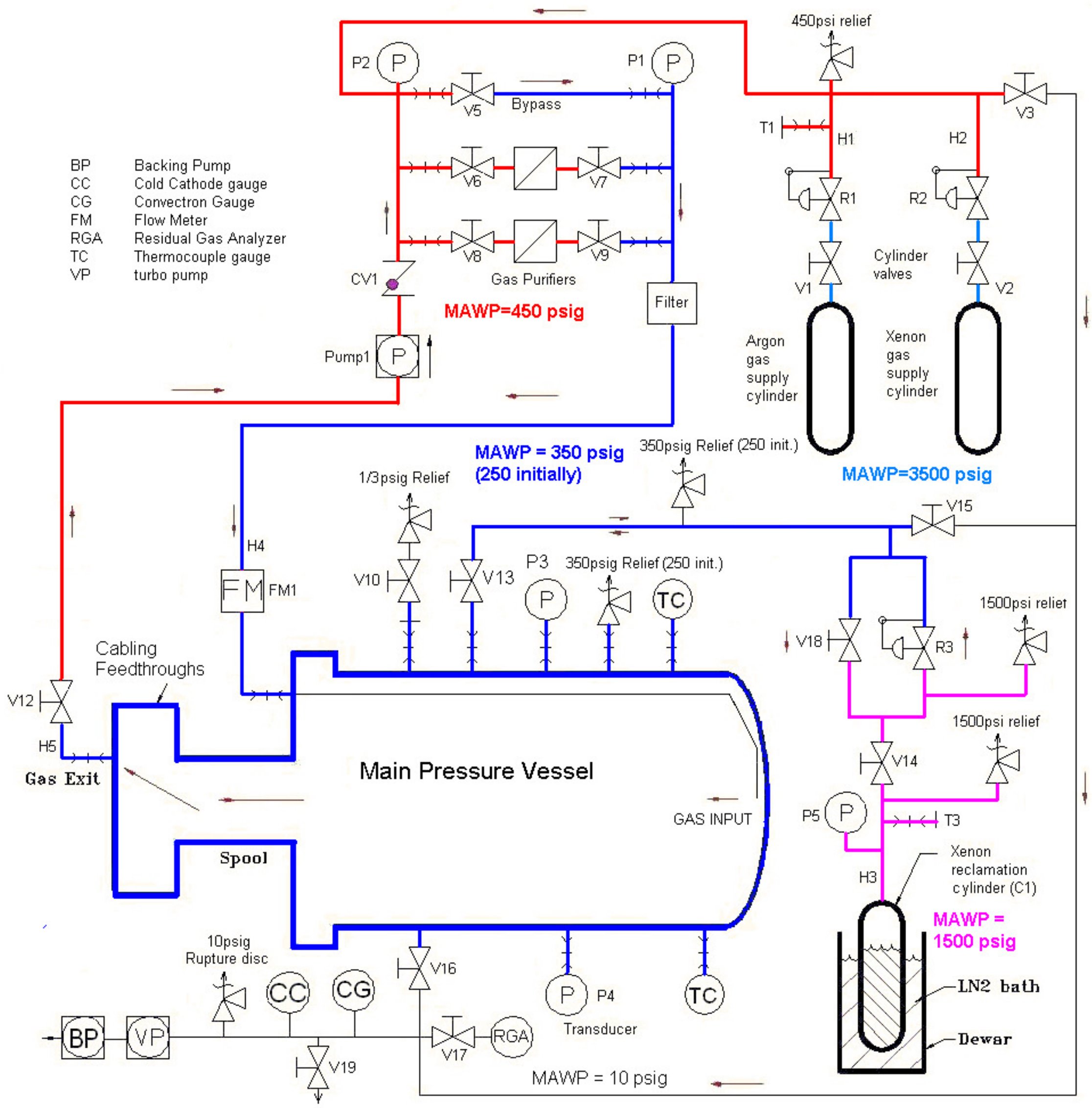


Fig. 5 Gas System Schematic

Operation of the system is treated in detail in section 8, Gas System below, and in the AHD (to be prepared). The basic sequence is essentially:

1. All valves, except the gas cylinder and vacuum purge valves, are opened (including the reclamation cylinder) and the system is pumped down to a high vacuum. Argon may be used for an initial flush, or to provide for a purge when the system is opened.

2. The vacuum valve is then shut and the system (including reclamation cylinder) is filled with Xenon to 300 psig (225 initially) at room temperature.

3. The dewar is filled with LN2; this freezes out the Xenon into the reclamation cylinder, which is then valved off.

4. The main system is refilled with Xenon to to 50 psig, and step 3 is repeated. This step charges the reclamation cylinder with a small amount of extra Xenon to provide for quicker refilling of the main system.

5. To fill the main system at the desired pressure, the reclamation cylinder is opened and regulated flow is let back into the vessel until the desired pressure is reached. Heaters on the reclamation cylinder may be needed to warm

the gas, as it will cool upon expansion; a maximum temp. of 50C is used. The gas will cool upon expanding through the regulator, and the pressure will be lower than 300 psig (225 psig initially) until the gas warms up to room temperature. Line heaters on the refill line may be needed to reduce the amount of time needed to come back to room temperature.

6. The pump is then operated to circulate the Xenon through the main pressure vessel and through the gas purifiers. The gas flow rate is varied as needed, using the pump controller, and only one gas purifier is used at a time. ~~The reclamation cylinder valve is left open during operation.~~

7. To open the main pressure vessel for service (to TPC), step 3 is repeated.

8. After closing the main pressure vessel after TPC service and pumping it down to high vacuum, step 5 is repeated.

Pressure Safety Assurance There are five pressure zones in the system:

1. Main Vessel with attached components, 350 psig MAWP, protected by 350 psig relief valve on main vessel (a 250 psig relief valve will be installed initially until high pressure SHV-20 connectors are procured and installed).
2. Gas supply and purifier loops 1000 psig MAWP, protected by 450 psig relief valve.
3. Reclamation cylinder, 3000 psig MAWP, protected by 1500 psig relief valve.
4. The gas supply cylinders themselves have their burst disks behind their valves, per standard gas cylinder practice.
5. The vacuum system has a 10 psig burst disk on the vacuum side.

Hazards Analysis

There are no toxic, flammable, biological, or radioactive gasses or materials inside the vessel with the possible exception of some small low intensity sealed gamma ray sources. The inside detector is composed of common metals, Teflon, Mylar, Kapton and PEEK polymers, glass, signal cabling and some semiconductor ICs. There will be high voltage components inside, operating as high as +/-20 kV, but at low stored energy, and there will be no organic liquids, gases, or aerosols, and no oxygen present when operating, so there is no explosion hazard. There are 19 photomultiplier tubes (PMTs) 1 inch diameter by 2 inches long which are known to withstand use at 20 bar; they have the possibility of imploding under excessive pressure, but this is not expected to create any hazard from excessive transient pressure, or other hazard since they are surrounded by a dense gas, not a liquid, as is the case in some neutrino detectors. These PMTs will be hydrostatically pressure tested before use at 110-125% MOP = 375 psig (275 psig initially). There are no toxic or radioactive materials inside the PMT's. These PMTs are the limiting factor for the experiment, and set the MOP to 300 psig. There are, initially ~~two~~ three SHV-20 high voltage feedthrus that are rated for use at 250 psi; this is the lowest MAWP of the entire system and thus a 250 psig relief valve will be initially installed on the pressure vessel until a high pressure (800 psig MAWP) version of this feedthrough is procured; at which time the MAWP will be changed to 350 psig.

There will be people present near the vessel when it is under full pressure. Under PUB3000, sec 7.6.1, it is classified as a High Hazard Pressure System, since there are gas pressures above 150 psig. An AHD is not required for the Xenon or Argon gases, nor any of the other materials inside, but there may be pressure and process hazards, so an AHD will be formulated.

Main Vessel Description

The vessel is constructed from Schedule 80 316L S.S. pipe and the flanges and heads are 304 S.S. (if not 304L). There are no brittle materials used. Welds were made by ASME certified welders according to the LLNL Note. Welds were designed with an efficiency factor of 0.7 to eliminate the need to radiograph welds.

As mentioned above, the main vessel has a Maximum Operating Pressure (MOP) of 850 psig when used with a specially made blank flat head which seals against the vessel flange with a C-type face gasket. Maximum allowable Pressure (MAWP) is 976 psig with this head. This vessel and head combination has been pressure tested to 1.5xMAWP=1467 psig. However there is no plan to operate the vessel at LBNL using this head.

It has an MOP of 350 psig when used with a different specially made flat head (labeled AAA-99-104240-00) which has a number of openings for instrumentation, each of which seals with a CF-type (conflat) flange. This flat head is not a standard CF type flange but has increased thickness and uses double the number of clamping bolts. It seals using a standard CF gasket and knife edge design, however. Maximum allowable Pressure (MAWP) is 406 psig. It has been pressure tested to 1.5xMAWP = 609 psig with this head (openings blanked off).

The vessel can only, and will only be used at LBNL with the 350 psig MOP head. There are a number of valves, pipes and electrical feedthru's that will attach to the head and vessel; all will be either rated by the manufacturer for 350 psig operation (MAWP at min.), and, if not, will be analyzed for pressure safety and pressure tested, either in conjunction with this vessel or separately. The strength of this vessel and head have no dependency on any attached components, nor do any attached components rely on this vessel or head for strength.

As stated above, there are no toxic, flammable, biological, or radioactive gasses or materials used inside the vessel with the exception of some small low intensity sealed gamma sources. Argon gas will be used as a purge gas, most likely at low pressure but perhaps up to the MOP e.g. for leak checking. There is a cold probe welded to the main tank vessel which was used to condense Xenon inside the vessel, using a surrounding dewar of LN2, however, there are no plans at LBNL to use this feature, and it will be labeled to prohibit use.

As stated above, there are also some new components which will be attached to the vessel and flat head, some of which are pressure rated by the manufacturer, some which are not rated by the manufacturer but which are suitable for safely holding pressure, and some which will be designed and built by LBNL. These latter two categories are analyzed in this note for sufficient strength and will be proof tested separately.

LLNL Safety Note MESN99-020-OA (1999) shows calculations performed in accordance with ASME Pressure Vessel Code Section VIII-1-1997. The analysis appears to be fairly complete and correct with respect to ASME Pressure Vessel Code Section VIII-1-2007, which this author has access to. There is an analysis of the 350 psi MOP head which uses a non-ASME method involving stress concentration factors, however there is also an analysis based on ASME methods. This document is reproduced in the Appendix. Also in the Appendix are the two pressure test reports from LLNL, plus two notes on pressure capacity of CF flanges, one from LLNL and one from ANL.

What follows are basic calculations for this experimental system and additional calculations for the added components:

3. Basic System Calculations

Stored Energy, U, @ 350 psig MAWP

from PUB3000 , Chapter 7, Appendix E:

$$U = \frac{P_h V_h}{\gamma - 1}\left[1 - \left(\frac{P_l}{P_h}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

where:

$P_h := P_{MAWP} + 14.7\text{psi}$ $\quad P_h = 364.7\,\text{psi}$ $\quad P_l := 14.7\text{psi}$ $\quad \gamma := 1.666$ (for monatomic gases)

Volume includes vessel, cabling octagon, connecting spool, valve and gas system tubing:

$d_{ves} := 7.63\text{in}$	$l_{ves} := 13.5\text{in}$	main vessel inner dimensions
$d_{LNxt} := 2\text{in}$	$l_{LNxt} := 8\text{in}$	LN2 extension (cold probe)
$d_{oct} := 8\text{in}$	$l_{oct} := 3.0\text{in}$	Kimball octagon for cabling
$d_{spool} := 2\text{in}$	$l_{spool} := 10\text{in}$	connection spool, flat head to octagon
$d_{tubing} := 0.5\text{in}$	$l_{tubing} := 20\text{ft}$	gas system tubing and purifiers (est.)
$d_{valve} := 2\text{in}$	$l_{valve} := 4\text{in}$	high pressure volume of closed vacuum valve and tank stub
$d_{rc} := 3.43\text{in}$	$l_{rc} := 36\text{in}$	reclamation cylinder

$$V_h := \frac{\pi}{4}\cdot\left(d_{ves}{}^2\cdot l_{ves} + d_{LNxt}{}^2\cdot l_{LNxt} + d_{spool}{}^2\cdot l_{spool} + d_{oct}{}^2\cdot l_{oct} + d_{tubing}{}^2\cdot l_{tubing} + d_{valve}{}^2\cdot l_{valve} + d_{rc}{}^2 l_{rc}\right)$$

$V_h = 1.2\times 10^3\, in^3 \quad V_h = 19.9\,L \qquad V_{ves} := \frac{\pi}{4}d_{ves}{}^2\cdot l_{ves} \quad V_{ves} = 10.115\,L$

Stored Energy @ 350 psig MAWP

$$U_v := \frac{P_h\cdot V_h}{\gamma - 1}\left[1 - \left(\frac{P_l}{P_h}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad U_v = 54\,kJ$$

Mass of Xenon in System at operating pressure

$P_{MOP} = 300\,psi \quad R := 8.314 J\cdot mol^{-1}\cdot K^{-1} \quad T_{amb} := 300K \quad M_{a\_Xe} := 131.3gm\cdot mol^{-1}$

Critical Pressure, temperature of Xenon:

$P_{c\_Xe} := 58.40bar \quad T_{c\_Xe} := 15.6K + 273K$

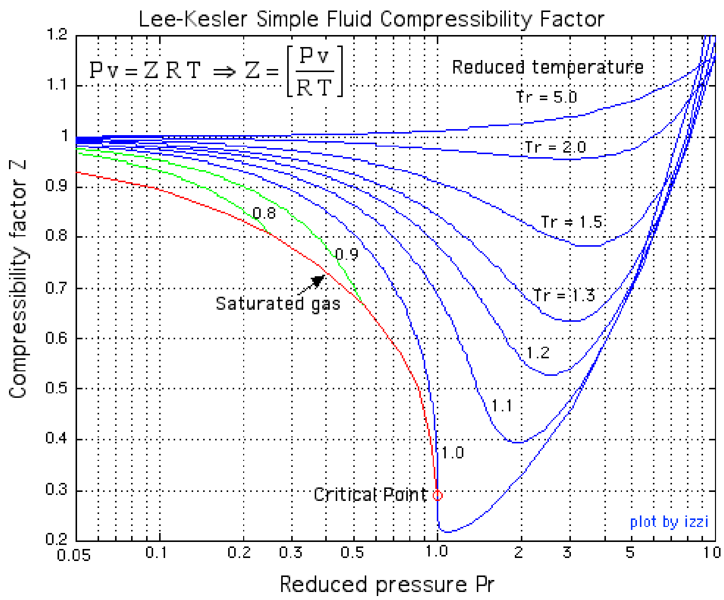
reduced pressure:

$P_r := \frac{315psi}{P_{c\_Xe}} \quad P_r = 0.361 \qquad T_r := \frac{T_{amb}}{T_{c\_Xe}} \qquad T_r = 1.04$

Compressibility Factor:

$Z_{Xe\_20bar} := 0.88$

from chart for pure gasses shown below



ref: <u>A Generalized Thermodynamic Correlation based on Three-Parameter Corresponding States</u>, B.I.Lee & M.G.Kesler, AIChE Journal, Volume 21, Issue 3, 1975, pp. 510-527' (secondary ref. from:http://www.ent.ohiou.edu/~-thermo/

Fig. 6 Compressibility Factor, pure gasses

Number of moles:

molar density

$$n_{Xe} := \frac{P_{MOP} \cdot V_h}{Z_{Xe\_20bar} \cdot R \cdot T_{amb}} \qquad n_{Xe} = 18.793\,\text{mol} \qquad \rho_{mol} := \frac{n_{Xe}}{V_h} \qquad \rho_{mol} = 0.942\,\frac{\text{mol}}{\text{L}}$$

Weight:

$$W_{Xe} := M_{a\_Xe} \cdot n_{Xe} \qquad W_{Xe} = 2.47\,\text{kg}$$

Volume of LXe in reclamation cylinder (at freeze-out)

density: $\rho_{LXe} := 3.05\,\frac{\text{gm}}{\text{mL}}$ @ boiling, 1 bar, -101.8C

$$V_{LXe} := \frac{W_{Xe}}{\rho_{LXe}} \qquad V_{LXe} = 0.809\,\text{L}$$

Xenon reclamation cylinder volume

$$V_{rc} := \frac{\pi}{4} \cdot d_{rc}^{\,2} \cdot l_{rc} \qquad V_{rc} = 5.451\,\text{L}$$

Pressure in Reclamation Cylinder

we need to guess initial value and iterate to find Z. From Lee-Kesler chart above it looks like it could be as low as 0.4, but heated to 50C it could be:

$$\rho_{mol\_rc} := \frac{n_{Xe}}{V_{rc}} \qquad \rho_{mol\_rc} = 3.448\,\frac{\text{mol}}{\text{L}}$$

$$P_{rc\_guess} := 3 \cdot P_{MOP} \qquad P_{rc\_guess} = 60.2\,\text{bar}$$

$$P_{r\_rc} := \frac{P_{rc\_guess}}{P_{c\_Xe}} \qquad P_{r\_rc} = 1.032$$

$$T_{hot} := (273 + 50)\text{K} \qquad T_{r\_hot} := \frac{T_{hot}}{T_{c\_Xe}} \qquad T_{r\_hot} = 1.12$$

from chart above:

$$Z_{Xe\_rb\_press} := .7$$

$$P_{rc} := \frac{n_{Xe} \cdot Z_{Xe\_rb\_press} \cdot R \cdot T_{amb}}{V_{rc}} \qquad P_{rc} = 58.4\,\text{bar} \qquad P_{rc} = 873\,\text{psi}$$

close enough to guess

Alternately, we can use a pressure density curve:

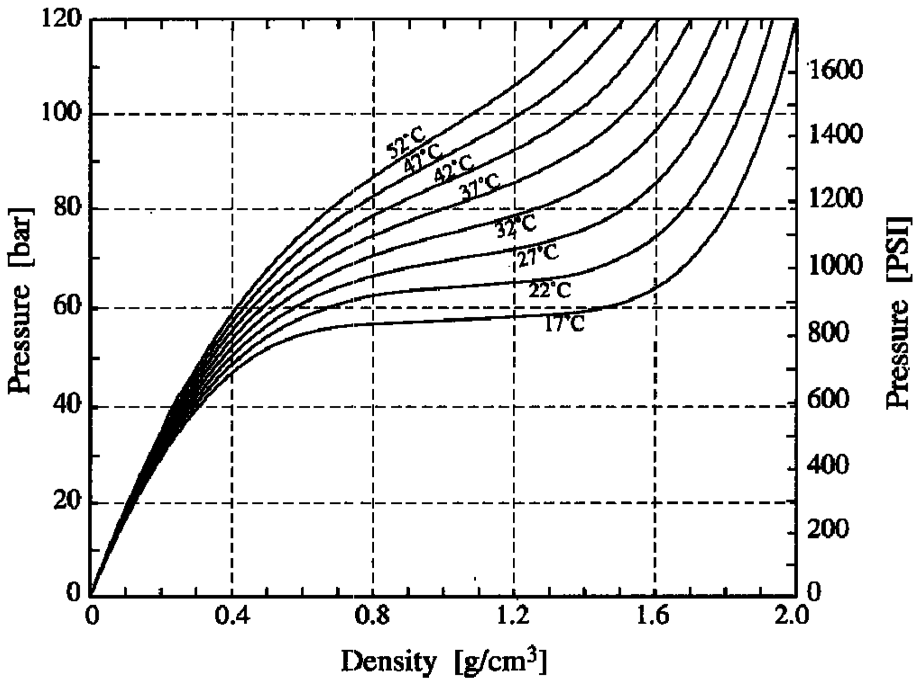


Fig. 7 Pressure-Density Curves for Xenon

ref :Thermophysical Properties of Neon, Argon, Krypton, and Xenon V.A. Rabinovitch, A.A.Vasserman, V.I Nedostup, L.I. Veksler, Hemisphere Publishing Co (1985) *via:* A Portable Gamma Ray Spectrometer using Compressed Xenon G.J. Mahler, et. al. IEEE Trans. Nuc. Sci. 45(3) p. 1029(1998)

for $\rho_{mass\_rc} := \rho_{mol\_rc} \cdot M_{a\_Xe}$ $\qquad \rho_{mass\_rc} = 0.453 \frac{gm}{cm^3}$

we find a maximum pressure of

$P_{max\_rc} := 63bar \qquad P_{max\_rc} = 941\,psi$ at 50C, which is the maximum temperature we expect to see. The gas purifiers have a maximum temperature of 40C.

Note: The reclamation cylinder will not be heated when condensing out, or when full. It will only be heated as needed to assist in refilling; this will only happen at a low pressure, after the vessel has been mostly refilled. As such it's typical maximum pressure will be determined by the room ambient temperature. Assuming this is 30C:

$P_{typ\_max\_rc} := 57bar \qquad P_{typ\_max\_rc} = 852\,psi$

Stored Energy in Reclamation cylinder

$$U_{rc} := \frac{P_{max\_rc} \cdot V_{rc}}{\gamma - 1}\left[1 - \left(\frac{P_1}{P_{max\_rc}}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad U_{rc} = 43\,kJ \qquad @50C$$

4. Vacuum Valve:

Valve is a Carten HF2000 process valve which is designed not only to hold high vacuum, but also to hold high pressure:

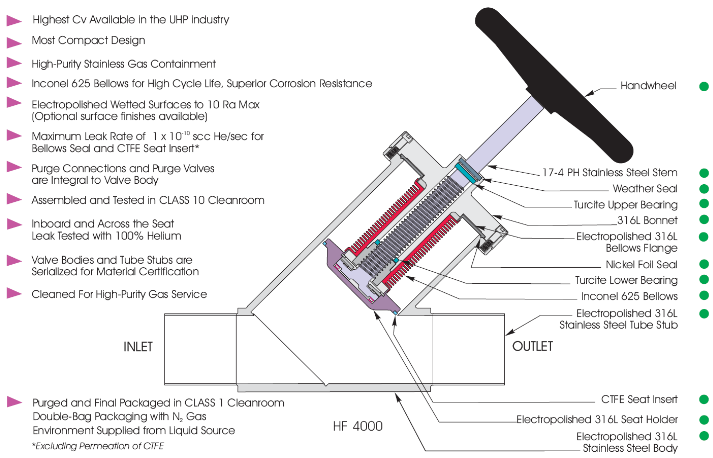
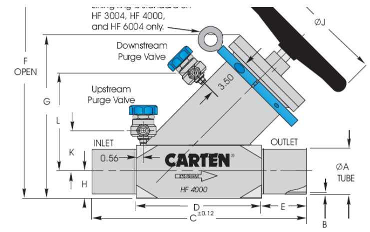


Fig. 8 Carten HF2000 process valve



Standard purge valve connection sizes are:
HF 500, HF 751, HF 1000, and HF 1501 = 1/4" purge connectors
HF 1502 and larger valves = 1/2" purge valves

CAT. NO.	A*	B*	C	D	E	F	G	H	J
HF 500	0.50	0.049	9.50 (241.1mm)	3.46 (87.9mm)	3.02 (76.7mm)	4.75 (120.7mm)	3.26 (82.8mm)	0.50 (12.7mm)	2.50 (63.5mm)
HF 751	0.75	0.065	12.86 (326.6mm)	4.8 (121.9mm)	4.03 (102.4mm)	7.97 (202.4mm)	5.86 (148.8mm)	0.75 (19.1mm)	3.94 (100.1mm)
HF 1000	1.00	0.065	10.84 (275.3mm)	4.8 (121.9mm)	2.98 (75.7mm)	7.97 (202.4mm)	5.86 (148.8mm)	0.75 (19.1mm)	3.94 (100.1mm)
HF 1501	1.50	0.065	14.76 (374.9mm)	4.8 (121.9mm)	4.98 (126.5mm)	7.97 (202.4mm)	5.86 (148.8mm)	0.75 (19.1mm)	3.94 (100.1mm)
HF 1502	1.50	0.065	17.16 (435.9mm)	6.98 (177.3mm)	5.09 (129.3mm)	13.15 (340.0mm)	8.86 (225.0mm)	1.31 (33.3mm)	7.87 (199.9mm)
HF 2000	2.00	0.065	15.24 (387.1mm)	6.98 (177.3mm)	4.13 (104.9mm)	13.15 (340.0mm)	8.86 (225.0mm)	1.31 (33.3mm)	7.87 (199.9mm)

Fig. 9 Carten HF2000 process valve dimensions

Note: manufacturer has agreed to weld valve to a 4 5/8" CF flange and pressure certify to 350 psig MOP. Nevertheless, here are some calculations. We see that the pressure capability of this valve, in the closed position will be determined by the wall thickness B. From ASME Section VIII UG-27 Thickness of Shells under Internal Pressure:

(c) Cylindrical Shells. The minimum thickness or maximum allowable working pressure of cylindrical shells shall be the greater thickness or lesser pressure as given by (1) or (2) below.

(1) Circumferential Stress (Longitudinal Joints). When the thickness does not exceed one-half of the inside radius, or P does not exceed $0.385SE$, the following formulas shall apply:

$$t = \frac{PR}{SE - 0.6P} \quad \text{or} \quad P = \frac{SEt}{R + 0.6t} \qquad (1)$$

(2) Longitudinal Stress (Circumferential Joints).[16] When the thickness does not exceed one-half of the inside radius, or P does not exceed $1.25SE$, the following formulas shall apply:

$$t = \frac{PR}{2SE + 0.4P} \quad \text{or} \quad P = \frac{2SEt}{R - 0.4t} \qquad (2)$$

MAWP

Weld efficiency

$P_{MAWP} = 350\ \text{psi}$

$E_w := 0.7$ (est.)

Maximum Allowable Stress, 304 stainless steel:

Pipe and Tube:

From ASME Pressure Vessel Code (2007) Section II, Materials

TABLE 1A (CONT'D)
SECTION I; SECTION III, CLASSES 2 AND 3;* SECTION VIII, DIVISION 1; AND SECTION XII
MAXIMUM ALLOWABLE STRESS VALUES *S* FOR FERROUS MATERIALS
(*See Maximum Temperature Limits for Restrictions on Class)

Line No.	Nominal Composition	Product Form	Spec No.	Type/Grade	Alloy Designation/ UNS No.	Class/ Condition/ Temper	Size/Thickness, in.	P-No.	Group No.
15	18Cr–8Ni	Smls. & wld. pipe	SA-312	TP304	S30400	...	...	8	1
16	18Cr–8Ni	Smls. & wld. pipe	SA-312	TP304	S30400	...	...	8	1
17	18Cr–8Ni	Wld. pipe	SA-312	TP304	S30400	...	...	8	1
18	18Cr–8Ni	Wld. pipe	SA-312	TP304	S30400	...	...	8	1

TABLE 1A (CONT'D)
SECTION I; SECTION III, CLASSES 2 AND 3;* SECTION VIII, DIVISION 1; AND SECTION XII
MAXIMUM ALLOWABLE STRESS VALUES *S* FOR FERROUS MATERIALS
(*See Maximum Temperature Limits for Restrictions on Class)

Line No.	Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding													
	–20 to 100	150	200	250	300	400	500	600	650	700	750	800	850	900
15	20.0	...	20.0	...	18.9	18.3	17.5	16.6	16.2	15.8	15.5	15.2	14.9	14.6
16	20.0	...	16.7	...	15.0	13.8	12.9	12.3	12.0	11.7	11.5	11.2	11.0	10.8
17	17.0	...	17.0	...	16.1	15.5	14.8	14.1	13.8	13.5	13.2	12.9	12.6	12.4
18	17.0	...	14.2	...	12.7	11.7	11.0	10.4	10.2	10.0	9.8	9.6	9.4	9.2

pg. 90 pg. 92

note: lower 17 ksi values include joint efficiency E= 0.85 (N.A. here)

$S_{TP304} := 20\text{ksi}$

Flange is fabricated (typically) from 304 plate. Strength of 304 plate, also from Section II, Materials pgs. 90,92:

Line No.	Nominal Composition	Product Form	Spec No.	Type/Grade	Designation/ UNS No.	Condition/ Temper	Size/Thickness, in.	P-No.	Group No.
1	18Cr–8Ni	Plate	SA-240	302	S30200	...	...	8	1
2	18Cr–8Ni	Plate	SA-240	302	S30200	...	...	8	1
3	18Cr–8Ni	Plate	SA-240	304	S30400	...	...	8	1
4	18Cr–8Ni	Plate	SA-240	304	S30400	...	...	8	1

Line No.	Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding													
	–20 to 100	150	200	250	300	400	500	600	650	700	750	800	850	900
1	20.0	...	20.0	...	18.9	18.3	17.5	16.6	16.2	15.8	15.5	...	...	...
2	20.0	...	16.7	...	15.0	13.8	12.9	12.3	12.0	11.7	11.5	...	...	...
3	20.0	...	16.7	...	15.0	13.8	12.9	12.3	12.0	11.7	11.5	11.2	11.0	10.8
4	20.0	...	20.0	...	18.9	18.3	17.5	16.6	16.2	15.8	15.5	15.2	14.9	14.6

$S_{304} := 20000\text{psi}$

wall thickness inner radius

$t_{neck} := .065\text{in}$ $R_{i\_neck} := 1.0\text{in}$

$$t_{neck\_min\_circ} := \frac{P_{MAWP} \cdot R_{i\_neck}}{S_{304} \cdot E_w - 0.6 \cdot P_{MAWP}} \qquad t_{neck\_min\_circ} = 0.025\,\text{in} \quad \text{OK}$$

$$t_{neck\_min\_long} := \frac{P_{MAWP} \cdot R_{i\_neck}}{2S_{304} \cdot E_w + 0.4P_{MAWP}} \qquad t_{neck\_min\_long} = 0.012\,\text{in} \quad \text{OK}$$

5. Spool

A connecting spool will be attached to the central 2.75" CF integral flange of the 350 psi MOP head. This spool will carry signal and power cabling to a Kimball Physics octagon vacuum chamber (AKA octagon) having (8) 2.75" CF ports. The spool has a 2.75" CF flange on one end and a 6" CF flange on the other end. To prevent additional loading of the tube from impact or handling forces applied to the octagon or attached cabling, the octagon will be secured by an angle bracket to the table top, which is a 3/4" thick aluminum plate. See figs 3, 4. We include moment from static weight of octagon and cabling per subsection UG-22 Loadings:

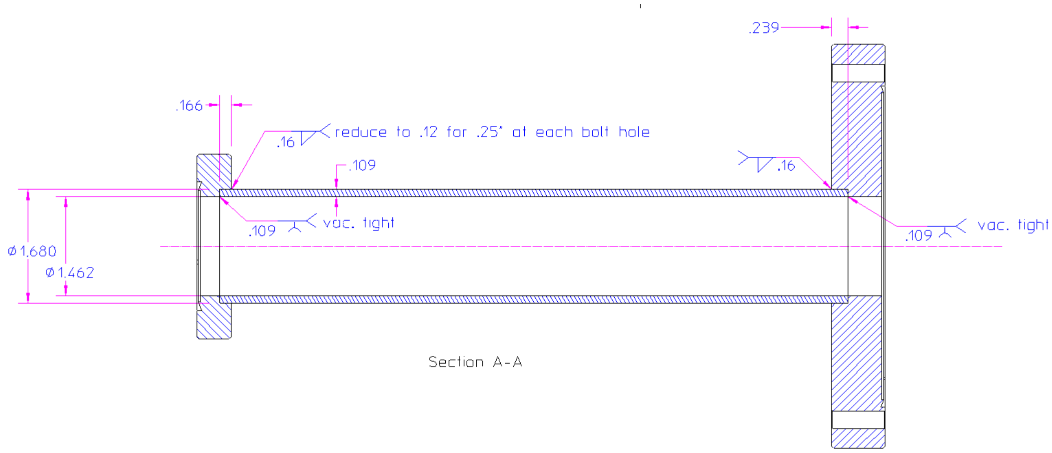


Fig. 10, Spool cross section

Spool Tube

Spool tube is a 1.25" schedule 10S pipe TP304 stainless steel, per ASME SA-312 specification (ASTM A 312)

spool tube diameter, length,thickness, inner radius:

$d_{o\_sp\_tube} := 1.66\text{in}$ $l_{tube} := 9.5\text{in}$ $t_{sp\_tube} := .109\text{in}$

$d_{i\_sp\_tube} := d_{o\_sp\_tube} - 2t_{sp\_tube}$ $R_{i\_sp\_tube} := 0.5d_{i\_sp\_tube}$ $R_{i\_sp\_tube} = 0.721\,in$

First we calculate minimum thickness required for tube to support weight of octagon and cables. This weight load occurs before the angle bracket restraint can be tightened and is "frozen in by the bracket" before pressure is applied. The load produces a bending moment on the tube which is highest where it is welded to the 2.75 in CF flange. This results in a longitudinal stress. We will then add this minimum thickness to that calculated for longitudinal stress due to pressure.

Weights:

octagon cabling and feedthrus CF flanges source insertion tube and flange

$W_{oct} := 13lbf$ $W_{cables} := 5lbf$ $W_{6in\_CF} := 5.5lbf$ $W_{so\_tube} := 2lbf$ $l_{oct} = 0.076\,m$

$$W_{cp\_tot} := W_{oct} + W_{cables} + 2 \cdot W_{6in\_CF} + W_{so\_tube}$$

$$M_{sp\_tube} := \left(l_{tube} + 0.5l_{oct}\right) \cdot W_{cp\_tot} \qquad M_{sp\_tube} = 341\,lbf \cdot in$$

$$I_{sp\_tube} := \frac{\pi}{64}\left(d_{o\_sp\_tube}^{\ 4} - d_{i\_sp\_tube}^{\ 4}\right) \qquad I_{sp\_tube} = 0.16\,in^4$$

$$\sigma_{sp\_tube\_mom} := \frac{M_{sp\_tube} \cdot 0.5d_{o\_sp\_tube}}{I_{sp\_tube}} \qquad \sigma_{sp\_tube\_mom} = 1763\,psi$$

Since ASME Pressure Vessel code calculates required thickness, we can perform a similar calculation for the minimum thickness required to withstand the applied bending moment and add this thickness to that require for pressure containment. Using an alternative approximate formula for moment of Inertia, I (using average diameter and thickness):

$$d_{avg\_sp\_tube} := 0.5\left(d_{i\_sp\_tube} + d_{o\_sp\_tube}\right)$$

$$I_{sp\_tube2} := \frac{\pi}{16} d_{avg\_sp\_tube}^{\ 3} \cdot t \;\blacksquare$$

Note: Equations (assignments) which have a small black square in their upper right corner are disabled (not active).

$$\sigma := \frac{Mc}{I} \;\blacksquare \qquad \sigma := \frac{M \cdot c}{\frac{\pi}{16} \cdot d^3 t} \;\blacksquare \qquad \sigma := S \cdot E \;\blacksquare$$

Solving for t (we need weld efficiency E): $E_{w\_fw} := 0.55$ double fillet weld from Table UW-12 (see weld calc below)

$$t_{sp\_tube\_M} := \frac{M_{sp\_tube} \cdot 0.5d_{avg\_sp\_tube}}{\frac{\pi}{16} d_{avg\_sp\_tube}^{\ 3} \cdot S_{TP304} \cdot E_{w\_fw}} \qquad t_{sp\_tube\_M} = 0.033\,in$$

Minimum tube thickness required for pressure load, as above, from UG-27:

$$t_{sp\_tube\_min\_circ} := \frac{P_{MAWP} \cdot R_{i\_sp\_tube}}{S_{TP304} \cdot E_{w\_fw} - 0.6 \cdot P_{MAWP}} \qquad t_{sp\_tube\_min\_circ} = 0.023\,in \qquad \text{OK}$$

$$t_{sp\_tube\_min\_long} := \frac{P_{MAWP} \cdot R_{i\_sp\_tube}}{2S_{TP304} \cdot E_{w\_fw} + 0.4P_{MAWP}} \qquad t_{sp\_tube\_min\_long} = 0.011\,in \qquad \text{OK}$$

Adding the two minimum thicknesses required for longitudinal stress:

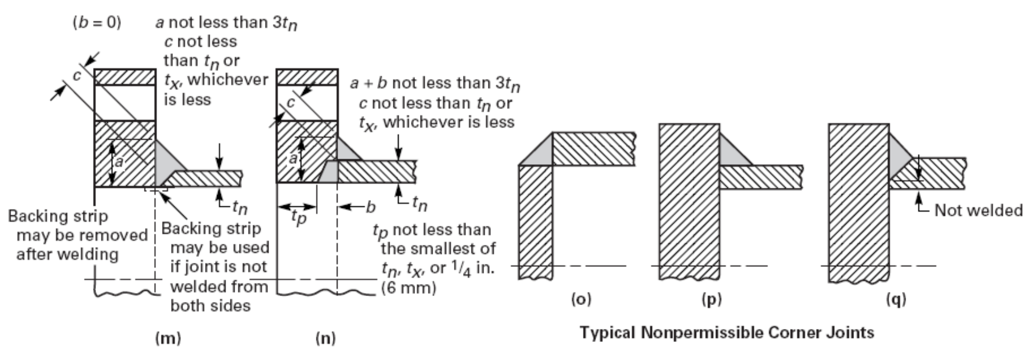
$t_{sp\_tube\_long\_total} := t_{sp\_tube\_min\_long} + t_{sp\_tube\_M}$ $\quad t_{sp\_tube\_long\_total} = 0.044\,in$ OK

This total required thickness is greater than that required for circumferential pressure, but still less than actual thickness.

Weld design:

From fig. UW-12 welds on both ends of tube are type 4 double full fillet welds, Category C weld (subsection UW-9 Design of Welded Joints , fig. UW-3) of type (n) below and must conform to rules in the figure

FIG. UW-13.2 ATTACHMENT OF PRESSURE PARTS TO FLAT PLATES TO FORM A CORNER JOINT (CONT'D)



Typical Bolted Flange Connections
c, t_n, and t_x are as defined in 2-3

weld dimensions:

outer $\quad$ inner

$h_{o\_sp} := .16in$ $\quad h_{i\_sp} := .082in$

dimensions for fig (n) above:

$c_{sp} := \frac{\sqrt{2}}{2} h_{o\_sp}$ $\quad c_{sp} = 0.113\,in$ $\quad t_{n\_sp} := t_{sp\_tube}$

$a_{sp} := t_{sp\_tube} + h_{o\_sp}$ $\quad a_{sp} = 0.269\,in$ $\quad b_{sp} := h_{i\_sp}$

weld criteria for fig (n) above:

$c_{sp} = 0.113\,in$ > $t_{n\_sp} = 0.109\,in$ OK

$a_{sp} + b_{sp} = 0.351\,in$ > $3t_{n\_sp} = 0.327\,in$ OK

CF flange calcs

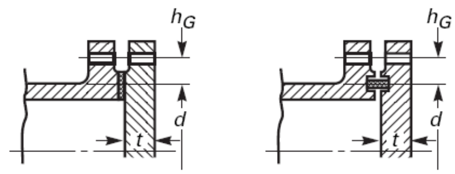
First we consider blank flanges, then consider those with central openings no larger that 0.5D; these are both considered flat unstayed heads. This is the case for the 6 in CF flange of the spool connecting to the octagon, and also for the 6 inch CF flange on the back of the octagon, which will have a central 2.75CF (1.5in dia) opening. From subsection UG-34, Unstayed Flat Heads and Covers :

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t = d\sqrt{CP/SE} \qquad (1)$$

except when the head, cover, or blind flange is attached by bolts causing an edge moment [sketches (j) and (k)] in which case the thickness shall be calculated by

$$t = d\sqrt{CP/SE + 1.9Wh_G/SEd^3} \qquad (2)$$



$C = 0.3$
[Use Eq. (2) or (5)]
(j)

$C = 0.3$
[Use Eq. (2) or (5)]
(k)

Eq. 2 is applicable and we can use mathCAD's ability to analyze a large number of CF flanges simultaneously. The following calculations are parallel calculations (not matrix or vector calcs). Read straight across from desired flange size, OD_{CF} , in order to find associated quantities:

Flange size — Number of bolts — Knife edge diameter

$$OD_{CF} := \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad N_{CF} := \begin{pmatrix} 6 \\ 4 \\ 6 \\ 8 \\ 8 \\ 10 \\ 16 \\ 20 \\ 24 \\ 30 \end{pmatrix} \qquad d_{ke} := \begin{pmatrix} .72 \\ 1.09 \\ 1.65 \\ 2.20 \\ 3.04 \\ 3.35 \\ 4.54 \\ 6.54 \\ 8.54 \\ 11.35 \end{pmatrix} in$$

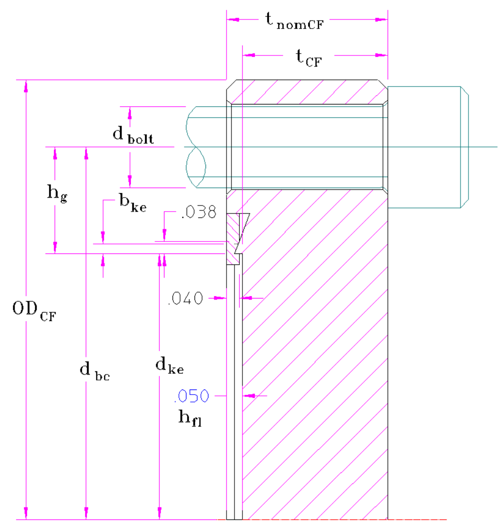


Fig. 11 CF (conflat) flange dimensions

Flange size — Bolt circle dia. — Flange thickness — Bolt dia. — Height of bolt flange

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad d_{bc} := \begin{pmatrix} 1.062 \\ 1.625 \\ 2.312 \\ 2.85 \\ 3.628 \\ 4.03 \\ 5.128 \\ 7.128 \\ 9.128 \\ 12.06 \end{pmatrix} in \qquad t_{nomCF} := \begin{pmatrix} .285 \\ .47 \\ .5 \\ .62 \\ .68 \\ .75 \\ .78 \\ .88 \\ .97 \\ 1.12 \end{pmatrix} in \qquad d_{bolt} := \begin{pmatrix} .16 \\ .25 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .375 \end{pmatrix} in \qquad h_{fl} := \begin{pmatrix} .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \end{pmatrix} in$$

Bolt Load W:

We have several choices here, use the flange mfr.'s recommended bolt torque (T_{CF_MDC}), a torque found to pull flanges together (T_{CF_ANL}; see ANL note in Appendix) or use a value bolt torque (T_{rec}) back calculated to withstand the required pressure (times a suitable safety factor) without exceeding ASME allowable flange stress for loose flanges, which the 2.75 OD flange is. This is the controlling configuration, and is treated in the section below for Flanges with Large Central Openings. It turns out that higher torques are not necessarily better, the additional edge moment creates flange stresses higher than allowed. If the joint fully closes (flange faces fully touching under bolts), then the joint design is changed and edge moment is reduced or eliminated, however this is not a reliably achievable condition. The Appendix contains a note testing this method (no pressure tests however). We use this back calculated torque T_{rec} (recommended torque) below by assigning T_{rec} to T_{CF}: Note that under ASME code Section VIII, non mandatory Appendix S-1 certain allowances can be made to use higher than calculated bolt tensions if needed in order to achieve sealing under unusual circumstances. Use of annealed copper gaskets is recommended. Sustituting elastomeric O-rings (Vition, Buna-N, PTFE) is also possible; this eliminates edge moments from tightening. The procedure here will be to start by using annealed Copper gaskets; tightening bolts initially to T_{rec} then leak checking during pressure testing; additional torque is to be used only if necessary. Safety will achieved via the pressure test, and also by noting the previous experience and testing of others as documented in the LLNL Safety Note END 92-072 (in Appendix), showing that CF flanges will leak before breaking from pressure loads.

Torques, bolt

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad T_{CF\_ANL} := \begin{pmatrix} 40 \\ 163 \\ 163 \\ 197 \\ 217 \\ 190 \\ 217 \\ 246 \\ 260 \\ 330 \end{pmatrix} lbf \cdot in$$

from ref. 3, ANL CF pressure capacity document, torque required to pull CF flanges fully together

$$T_{CF\_MDC} := \begin{pmatrix} 7 \\ 12 \\ 15 \\ 15 \\ 15 \\ 15 \\ 15 \\ 15 \\ 15 \\ 26 \end{pmatrix} lbf \cdot ft \qquad T_{rec} := \begin{pmatrix} .65 \\ 5 \\ 4 \\ 6.5 \\ 12.5 \\ 9.5 \\ 9.5 \\ 10.5 \\ 11 \\ 15 \end{pmatrix} lbf \cdot ft$$

Torque Used:

$$T_{CF} := T_{rec}$$

Total Bolt Load:

$$W_{CF} := \overrightarrow{\frac{N_{CF} \cdot 5T_{CF}}{d_{bolt}}}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad W_{CF} = \begin{pmatrix} 1463 \\ 4800 \\ 4608 \\ 9984 \\ 19200 \\ 18240 \\ 29184 \\ 40320 \\ 50688 \\ 72000 \end{pmatrix} lbf$$

Flange Thickness, effective:

$$t_{CF} := \overrightarrow{\left(t_{nomCF} - h_{fl}\right)}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad t_{CF} = \begin{pmatrix} 0.235 \\ 0.42 \\ 0.45 \\ 0.57 \\ 0.63 \\ 0.7 \\ 0.73 \\ 0.83 \\ 0.92 \\ 1.07 \end{pmatrix} in$$

radial distance from gasket load center to bolt circle:

$$h_g := 0.5\overrightarrow{\left(d_{bc} - d_{ke}\right)}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} in \qquad h_g = \begin{pmatrix} 0.171 \\ 0.267 \\ 0.331 \\ 0.325 \\ 0.294 \\ 0.34 \\ 0.294 \\ 0.294 \\ 0.294 \\ 0.355 \end{pmatrix} in$$

$$E := 1 \qquad C_j := 0.3$$

Solving for pressure in eq (2) above:

$$P_j := \overrightarrow{\frac{S_{304} \cdot E}{C_j}\left(\frac{t_{CF}^{\ 2}}{d_{ke}^{\ 2}} - \frac{1.9 \cdot W_{CF} \cdot h_g}{S_{304} \cdot E \cdot d_{ke}^{\ 3}}\right)}$$

$$P_j = \begin{pmatrix} 2858 \\ 3619 \\ 2808 \\ 2545 \\ 1591 \\ 1866 \\ 1143 \\ 805 \\ 622 \\ 482 \end{pmatrix} psi$$

All pressures are greater than:
$P_{MAWP} = 350\ psi$
so all CF blank flanges are suitable for use, when torqued to T_{rec}

CF gasket calculations

From Appendix 2 Section VIII-Div. 1 Rules for Bolted Flange Connections with Ring type Gaskets subsection 2-5, Bolt Loads:

The required bolt load for the operating conditions W_{m1} is determined in accordance with eq. (1).

$$\begin{aligned} W_{m1} &= H + H_p \\ &= 0.785G^2P + (2b \times 3.14GmP) \qquad (1) \end{aligned}$$

(2) Before a tight joint can be obtained, it is necessary to seat the gasket or joint-contact surface properly by applying a minimum initial load (under atmospheric temperature conditions without the presence of internal pressure), which is a function of the gasket material and the effective gasket area to be seated. The minimum initial bolt load required for this purpose W_{m2} shall be determined in accordance with eq. (2).

$$W_{m2} = 3.14bGy \qquad (2)$$

where G is the gasket diameter

for flat copper gaskets (from Table 2-5.1):

$m_{Cu\_flat} := 4.75 \qquad y_{Cu\_flat} := 13000psi$

effective width b is taken to be 80% of the width of the interference (.0384 in) of the knife edge (to allow for less than full joint closure) and the gasket (.08" thk.):

$b_{ke} := 80\% \cdot .0384in$ .0384 in. measured from 2.75 in flange MDC CAD model; assume same for all flanges

$b_{ke} = 0.031\,in$

$G := d_{ke} + 2b_{ke}$ outer diameter of effective compressed gasket area

solving eq (1) above for maximum pressure, (in two stages, to allow concurrent calculation)

$$p_{m1} := \frac{1}{\overrightarrow{\left(0.785G^2 + 2\pi b_{ke} \cdot m_{Cu\_flat} \cdot G\right)}}$$

$$P_{m1} := \overrightarrow{\left(p_{m1} \cdot W_{CF}\right)}$$

and eq(2):

$$W_{m2} := 3.14b_{ke} \cdot G \cdot y_{Cu\_flat}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{in} \qquad P_{m1} = \begin{pmatrix} 1223 \\ 2290 \\ 1191 \\ 1640 \\ 1847 \\ 1487 \\ 1400 \\ 1001 \\ 768 \\ 639 \end{pmatrix} \text{psi} \qquad W_{m2} = \begin{pmatrix} 980 \\ 1444 \\ 2146 \\ 2836 \\ 3889 \\ 4278 \\ 5770 \\ 8278 \\ 10786 \\ 14310 \end{pmatrix} \text{lbf} \quad \text{compare-->} \quad W_{CF} = \begin{pmatrix} 1463 \\ 4800 \\ 4608 \\ 9984 \\ 19200 \\ 18240 \\ 29184 \\ 40320 \\ 50688 \\ 72000 \end{pmatrix} \text{lbf}$$

We see that the gasket preloading requirement W_{m2} is easily exceeded by the actual preload W_{CF}, and that the gaskets can theoretically hold far higher pressure than necessary (350 psi).

CF Blank Flange maximum opening diameter:

UG-39(b) Single and multiple openings in flat heads that have diameters equal to or less than one-half the head diameter may be reinforced as follows:

UG-39(b)(1) Flat heads that have a single opening with a diameter that does not exceed one-half the head diameter or shortest span, as defined in UG-34, shall have a total cross-sectional area of reinforcement for all planes through the center of the opening not less than that given by the formula

$$A = 0.5dt + tt_n(1 - f_{r1})$$

where d, t_n, and f_{r1} are defined in UG-37 and t in UG-34.

The 2.75 inch CF flange of the spool does not meet the above requirement,and is considered a loose flange, in a subsequent section. Nevertheless it is useful at this point to check to see if flanges that meet the requirement above are adequately reinforced for MAWP. Assume in formula above, that nozzle thickness is zero. First we determine minimum thickness required: t (here t_{min}). From subsection UG-34 :

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t = d\sqrt{CP/SE} \qquad (1)$$

except when the head, cover, or blind flange is attached by bolts causing an edge moment [sketches (j) and (k)] in which case the thickness shall be calculated by

$$t = d\sqrt{CP/SE + 1.9Wh_G/SEd^3} \qquad (2)$$

from sketches (j), (k) $C := 0.3$

weld efficiency: $E := 1$ (assume stock flanges only

$$t_{min\_CF} := \overrightarrow{\left(OD_{CF}\cdot\sqrt{\frac{C\cdot P_{MAWP}}{S_{304}\cdot E} + \frac{1.9W_{CF}\cdot h_g}{S_{304}\cdot E\cdot OD_{CF}^{\ 3}}}\right)}$$

minimum flange thickness thickness available for reinforcement

$$t_{min\_CF} = \begin{pmatrix} 0.165 \\ 0.285 \\ 0.304 \\ 0.389 \\ 0.475 \\ 0.49 \\ 0.57 \\ 0.69 \\ 0.816 \\ 1.051 \end{pmatrix} in \qquad t_{CF} - t_{min\_CF} = \begin{pmatrix} 0.07 \\ 0.135 \\ 0.146 \\ 0.181 \\ 0.155 \\ 0.21 \\ 0.16 \\ 0.14 \\ 0.104 \\ 0.019 \end{pmatrix} in$$

Area available for reinforcement

$$A_{rein\_CF} := \overrightarrow{\left[0.5 \cdot OD_{CF} \cdot \left(t_{CF} - t_{min\_CF}\right)\right]} \qquad A_{rein\_CF} = \begin{pmatrix} 0.047 \\ 0.144 \\ 0.201 \\ 0.306 \\ 0.349 \\ 0.487 \\ 0.48 \\ 0.558 \\ 0.518 \\ 0.125 \end{pmatrix} in^2$$

Maximum central opening diameter:

$$d_{i\_max\_CF} := \overrightarrow{\frac{A_{rein\_CF}}{t_{CF}}} \qquad d_{i\_max\_CF} = \begin{pmatrix} 0.199 \\ 0.342 \\ 0.446 \\ 0.537 \\ 0.554 \\ 0.695 \\ 0.658 \\ 0.672 \\ 0.563 \\ 0.117 \end{pmatrix} in$$

Note that the above bolt torques, calculated to give maxim allowable flange stress, essentially "use up" the reserve thickness in the flange so that only small central openings are permitted. These torques can be modified if needed to give larger central openings.

CF flanges with large central openings (ID>0.5OD):

For the small 2.75 inch flange on the spool (or for any central opening larger than that computed above) we consider this as a loose flange, per mandatory Appendix 2 of Section VIII- Div. 1, Rules for Bolted Flange Conections with Ring-type Gaskets, subsection 2-4 Circular Flange Types, as the attached tube does not contribute any strength to the flange. From subsection 2-6 Flange Moments:

Flange Moment

$$M_0 := W \cdot \frac{(C - G)}{2} \qquad M_0 := \overrightarrow{\left(W_{CF} \cdot h_g\right)} \qquad M_0 = \begin{pmatrix} 250 \\ 1284 \\ 1525 \\ 3245 \\ 5645 \\ 6202 \\ 8580 \\ 11854 \\ 14902 \\ 25560 \end{pmatrix} lbf \cdot in$$

Flange Stresses:

From mandatory Appendix 2, subsection 2-7 Flange Stresses:

First, compute several factors:

$$A := OD_{CF} \quad A = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{in}$$

Flange maximum inner diameter (from MDC catalogue)

$$ID_{CF} := \begin{pmatrix} .625 \\ 1 \\ 1.75 \\ 2 \\ 2.5 \\ 3 \\ 4 \\ 6 \\ 8 \\ 10.75 \end{pmatrix} \text{in} \qquad B := ID_{CF} \quad B = \begin{pmatrix} 0.625 \\ 1 \\ 1.75 \\ 2 \\ 2.5 \\ 3 \\ 4 \\ 6 \\ 8 \\ 10.75 \end{pmatrix} \text{in}$$

$$K := \overrightarrow{\frac{A}{B}} \qquad K = \begin{pmatrix} 2.128 \\ 2.125 \\ 1.571 \\ 1.688 \\ 1.8 \\ 1.542 \\ 1.5 \\ 1.333 \\ 1.25 \\ 1.233 \end{pmatrix}$$

$$Y := \overrightarrow{\left[\frac{1}{K-1}\left[0.66845 + 5.717\cdot\left(\frac{K^2\cdot\log(K)}{K^2-1}\right)\right]\right]} \qquad Y = \begin{pmatrix} 2.726 \\ 2.731 \\ 4.47 \\ 3.885 \\ 3.474 \\ 4.659 \\ 4.961 \\ 6.903 \\ 8.83 \\ 9.406 \end{pmatrix}$$

Bolt Torque used:

Flange Stresses (eqs. 9):

Tangential:

$$S_T := \overrightarrow{\frac{Y\cdot M_0}{t_{CF}{}^2 B}} \qquad S_T = \begin{pmatrix} 19751 \\ 19878 \\ 19240 \\ 19398 \\ 19764 \\ 19657 \\ 19969 \\ 19798 \\ 19433 \\ 19534 \end{pmatrix} \text{psi}$$

$S_{304} = 2 \times 10^4 \text{ psi}$

$S_T < S_{304}$ OK

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{in}$$

Radial and Axial stresses = 0

6. Kimball Physics Octagon

This is a 304 stainless steel machined octagonal vacuum chamber. It has eight 2.75 in CF ports, which will be used for feedthroughs and as above, we use subsection UG-27:

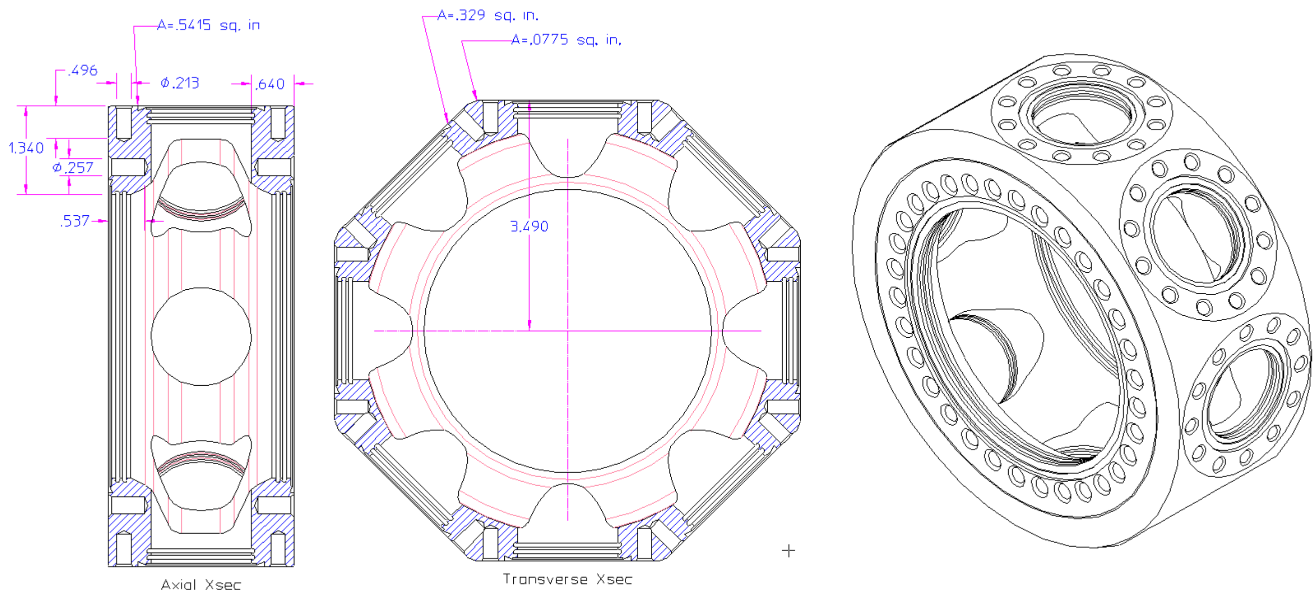


Fig. 12 Kimball Physics octagonal vacuum chamber ("octagon")

Areas, minimum of half cross sections:

$A_{circ} := 2 \cdot 0.5415 in^2$ $\quad A_{circ} = 1.083\,in^2$ $\qquad A_{long} := 4 \cdot (0.329 + 0.0775)\,in^2$ $\quad A_{long} = 1.626\,in^2$

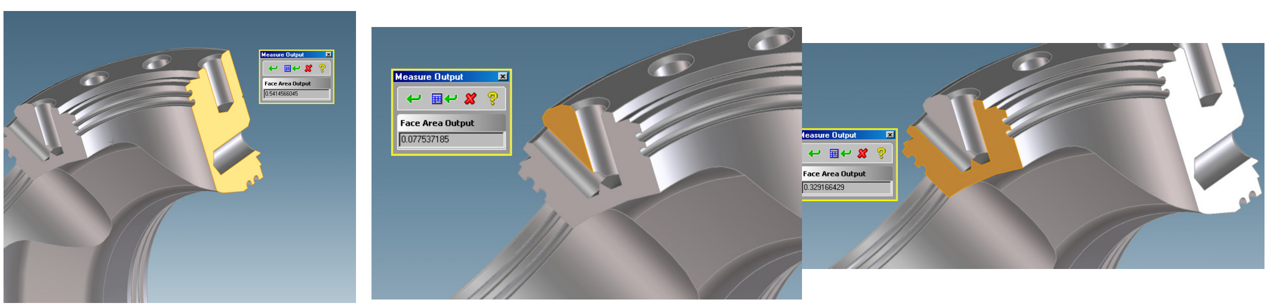


Fig. 13, section area measurements, octagon

Radii: $R_{i\_oct} := 3.5in$ note: this is largest radius (at the 2.75 in CF flanges)

Equivalent thicknesses (by dividing out radius)

$$t_{oct\_circ} := \frac{A_{circ}}{R_{i\_oct}} \qquad t_{oct\_circ} = 0.309\,in$$

$$t_{oct\_long} := \frac{A_{long}}{R_{i\_oct}} \qquad t_{oct\_long} = 0.465\,in$$

Weld Efficiency:

$E = 1$ machined, not welded

Minimum equivalent thicknesses:

$$t_{oct\_min\_circ} := \frac{P_{MAWP} \cdot R_{i\_oct}}{S_{304} \cdot E - 0.6 \cdot P_{MAWP}} \qquad t_{oct\_min\_circ} = 0.062\,in$$ compare --> $t_{oct\_circ} = 0.309\,in$

$$t_{oct\_min\_long} := \frac{P_{MAWP} \cdot R_{i\_oct}}{2S_{304} \cdot E + 0.4P_{MAWP}} \qquad t_{oct\_min\_long} = 0.031\,\text{in} \quad \text{compare -->} \quad t_{oct\_long} = 0.465\,\text{in}$$

7. Source Tube

This is a closed end tube welded to a 2.75 " CF flange for the purpose of introducing a small radioactive source into the chamber without opening up the vessel. The vessel pressure acts on the end and outer diameter of the tube, thus tube buckling is a possible failure mode. We use subsection UG-28 Thickness of Shells and Tubes Under External Pressure:

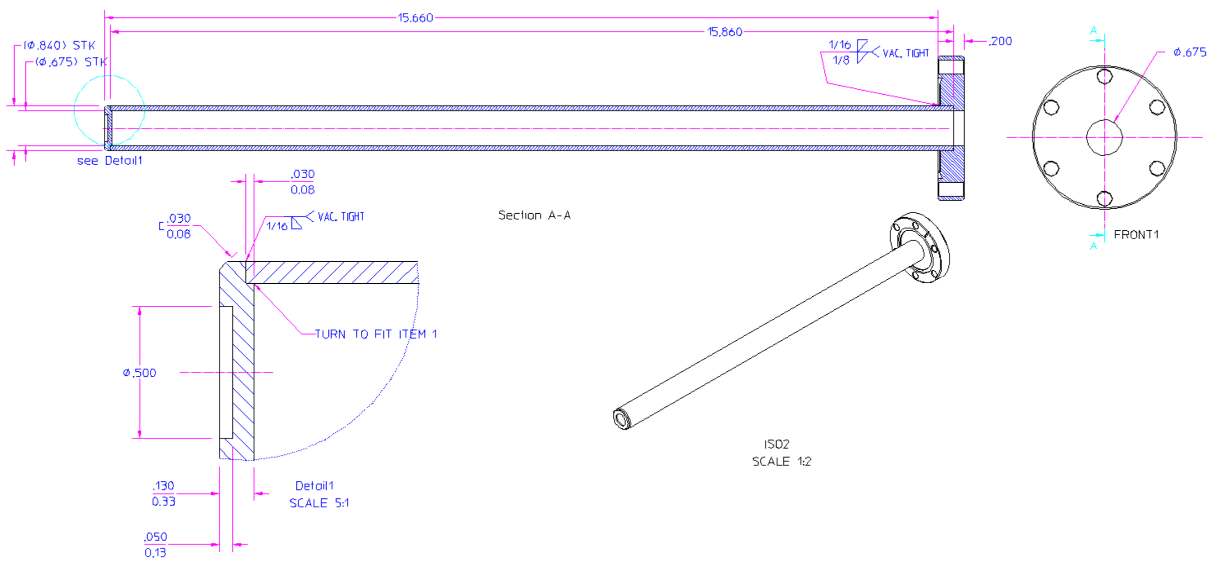


Fig 14, Source Insertion Tube

Tube is a 1/2 in. schedule 10S, ASME SA312 TP304 stainless pipe

$$D_{o\_st} := .84\text{in} \qquad L_{st} := 16\text{in} \qquad t_{st} := .083\text{in}$$

External pressure, maximum: $P_{st} := -P_{MAWP}$

The maximum allowable working external pressure is determined by the following procedure:

Compute the following two dimensionless constants:

$$\frac{L_{st}}{D_{o\_st}} = 19 \qquad \frac{D_{o\_st}}{t_{st}} = 10$$

From the above two quantities, we find, from fig. G in subpart 3 of Section II, the factor:

$$A_{st} := .012$$

Using the factor A in the applicable material (304 S.S.) chart (HA-1) in Subpart 3 of Section II, Part D, we find the factor B:

$$B_{st} := 14000\text{psi}$$

A08 FIG. G GEOMETRIC CHART FOR COMPONENTS UNDER EXTERNAL OR COMPRESSIVE LOADINGS (FOR ALL MATERIALS) [NOTE (14)]

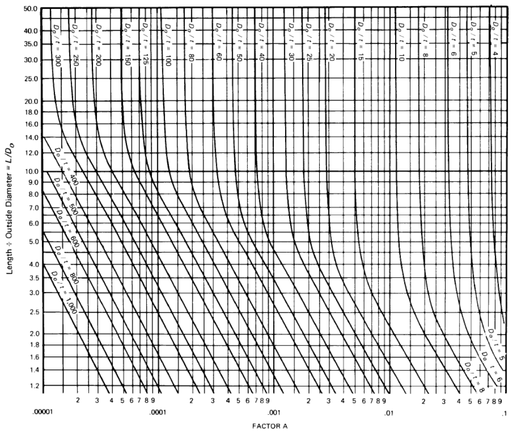
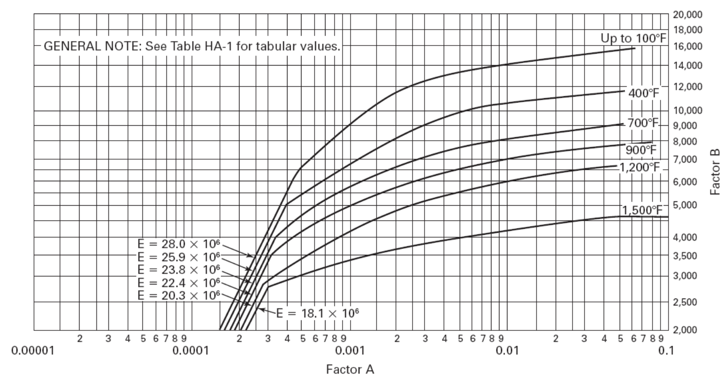


FIG. HA-1 CHART FOR DETERMINING SHELL THICKNESS OF COMPONENTS UNDER EXTERNAL PRESSURE DEVELOPED FOR AUSTENITIC STEEL 18Cr–8Ni, TYPE 304



The maximum allowable working external pressure is then given by :

$$P_{max\_st} := \frac{4B_{st}}{3\left(\frac{D_{o\_st}}{t_{st}}\right)} \qquad P_{max\_st} = 1844\,\text{psi} \quad \text{(external)}$$

$P_{max\_st} > 1.5P_{MAWP}$ so the source tube is safe from buckling under test pressure load

There is a bending moment on the tube where welded to the flange from the weight of the source collimator

Tube weight:

$$W_{st} := \rho_{SS}\cdot\pi\cdot D_{o\_st}\cdot t_{st}\cdot L_{st}\cdot g \qquad \rho_{SS} := 8\,\frac{gm}{cm^3} \qquad W_{st} = 1.013\,\text{lbf}$$

Collimator is either tungsten (19.3 gm/cc) or hevimet (19gm/cc). Maximum possible dimensions:

$$l_{col} := L_{st} \qquad d_{col} := D_{o\_st} - 2t_{st} \qquad d_{col} = 0.674\,\text{in} \qquad \rho_W := 19.3\,\frac{gm}{cm^3}$$

Weight of collimator :

$$W_{col} := \frac{\pi}{4}d_{col}^{\,2}\cdot l_{col}\cdot\rho_W\cdot g \qquad W_{col} = 3.98\,\text{lbf}$$

Moment on tube

Moment of Inertia, source tube

$$M_{st} := W_{col}\cdot\left(L_{st} - 0.5l_{col}\right) + W_{st}\cdot 0.5L \; M_{st} = 39.9\,\text{lbf}\cdot\text{in} \qquad I_{st} := \frac{\pi}{64}\left(D_{o\_st}^{\,4} - d_{col}^{\,4}\right) \qquad I_{st} = 0.014\,\text{in}^4$$

Stress, bending:

$$\sigma_{st} := \frac{M_{st}\cdot 0.5D_{o\_st}}{I_{st}} \qquad \sigma_{st} = 1172\,\text{psi} \qquad \text{negligible}$$

Axial Compressive Stress on tube:

The tube is relatively long and may be subject to Euler buckling. ASME code treats this as an alternate maximum allowable stress, rather than a maximum loading. From subsection UG-23 Maximum Allowable Stress Values, maximum allowable axial compressive stress, is smaller of :

S, from above (20 ksi) or:
B, as computed below

First, determine minimum required thickness (not sure why actual thickness is not used here):

$t_{st\_min} := .023\text{in}$ found using external presssure formula above for 500 psi (test pressure)

Then, determine the quantity:

$$A_{stl} := \frac{0.125}{\left[\frac{(0.5D_{o\_st})}{t_{st\_min}}\right]} \qquad A_{stl} = 0.007$$

From Subpart 3 of Section II, Part D, chart HA-1:

$$B_{st\_max} := 13500\text{psi}$$

Actual compressive stress (at test pressure of 1.5x MAWP):

$$\sigma_{st\_ax} := \frac{1.5P_{MAWP} \cdot D_{o\_st}}{4t_{st}} \qquad \sigma_{st\_ax} = 1328\,\text{psi} \quad \text{OK}$$

Welds are nonstructural, and do not carry pressure loads (other than vacuum); they are primarily for sealing.

Window stress (mtl:304SS):

From subsection UG-34, Unstayed Flat Heads and Covers :

$t_w := 1.5\text{mm} \quad R_w := .25\text{in}$

$E_w = 0.7$ (outside HAZ, but use any

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t = d\sqrt{CP/SE} \tag{1}$$

$$t_{min\_w} := 2R_w \cdot \sqrt{\frac{C \cdot P_{MAWP}}{S_{304} \cdot E_w}} \qquad t_{min\_w} = 1.1\,\text{mm} \quad \text{OK}$$

8. Gas System (in detail) (Tom Miller, designer)

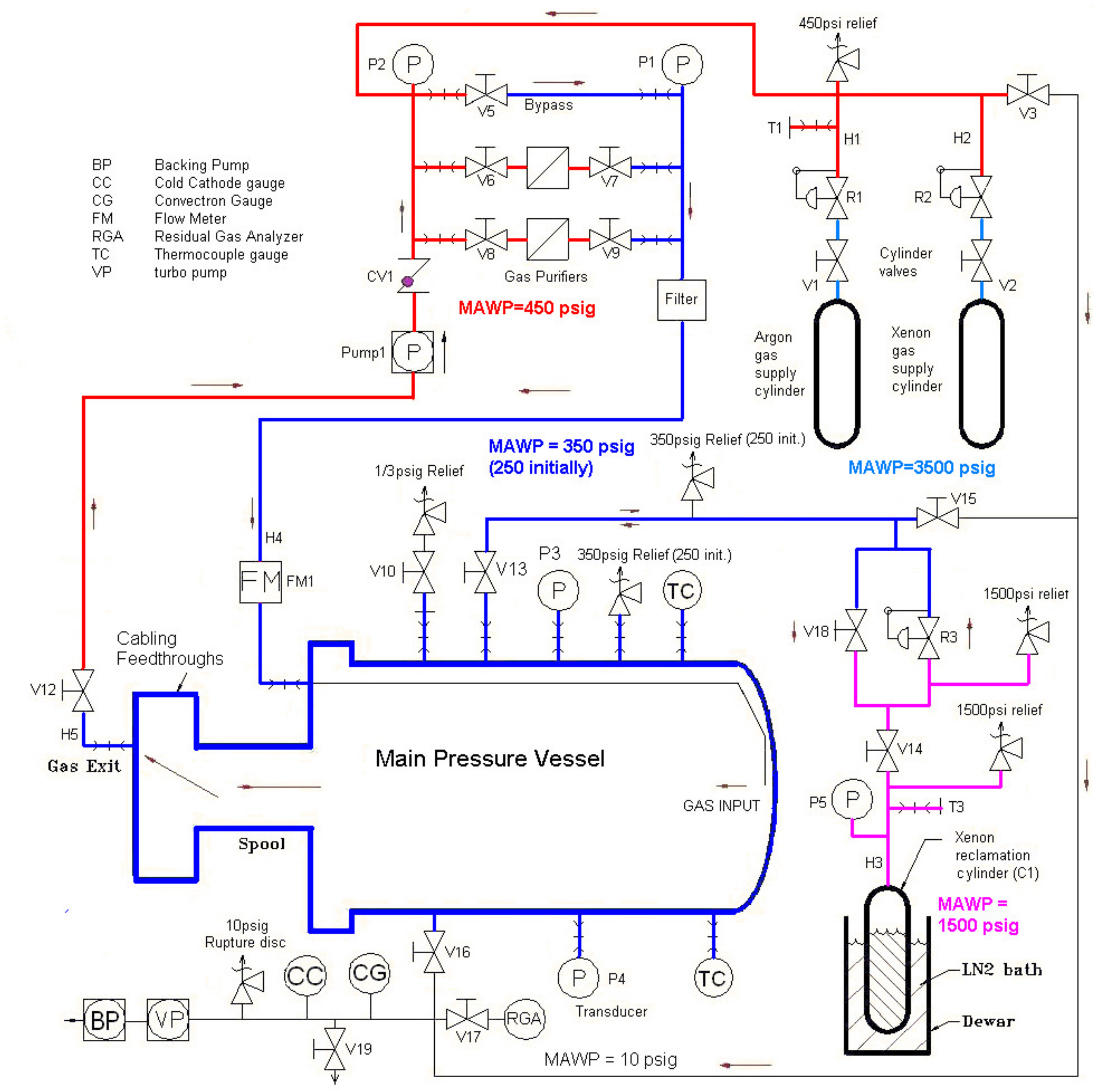


Fig. 15. Gas system (same as fig. 5)

~~Operation~~ **Description**:

This TPC (Time Projection Chamber) gas system is designed to circulate ~~purified~~ Xenon gas, through the pressure vessel and a purifier system at various pressures up to 300psig MOP (225 psig MOP initially with Ceramtec SHV-20 feedthroughs installed). It also includes a cryogenic Xenon reclamation section, as described previously. The AHD will initially specify only an 250psig MAWP (225psig MOP) with these feedthroughs, then it will be updated to the higher pressure MAWP (= 350 psig) only when these feedthroughs are replaced with higher pressure rated feedthroughs.

The gas system can be divided into 5 subsections, each having different MAWPs:

1.Gas supply subsystem MAWP =3500 psig (or gas cyl burst disk pressure)

2.Vacuum subsystem MAWP= 10 psig.

3.Pressure vessel and purifier downstream subsection,MAWP as above

4.Purifier upstream subsection; this MAWP is set 100 psi higher than the pressure vessel since Pump1 can deliver 130 psi maximum differential pressure if downstream flow is blocked; we desire not to vent Xenon gas should this occur (pump operated erroneously with [V3+V5+(V6 or V7)+(V8 or V9)] all closed.

5. Reclamation subsystem, MAWP =1500 psig

Operations

In operation, the procedures are sequential, unless otherwise indicated. There are steps inserted for checking valve status, **Valves** listed in **bold red** are **closed**; Valves listed in nonbold green are open. Note that there is no V4 or V11 ; these valves were present in an earlier draft configuration and have been removed. Valves have not been renumbered to avoid confusion.

1. Complete system pump-down

a. Close V1, V2 and V10. Open R1, ~~and~~ R2, and R3 one turn each.
b. Open V5, V13-V16, V18. DO NOT open V6-V9.
c. **V1 V2 ~~V3~~** V5 **V6 V7 V8 V9 V10 ~~V11~~ V12** V13 V14 V15 V16 **V17 V18 V19**
d. Turn on the backing pump and convectron gauge controller
e. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller. Open V3 and V12.
f. When the cold cathode gauge reads < 5e-5 torr, open V17 and turn on the RGA.
g. If the system pressure and RGA scan are acceptable, turn off the RGA. If not, continue to pump until the pressure improves to an acceptable level.
h. Close V3, V13-~~V17~~V18. Back off R1 ~~and~~ R2, and R3.
i. Turn off pumps and controllers.
j. **V1 V2 V3**- V5 **V6 V7 V8 V9 V10** V12 **V13 V14 V15 V16 V17 V18 V19**
k. Proceed to step 3.

2. System pump-down with xenon in the Xenon reclamation cylinder

a. Close V1, V2 and V10. Open R1 ~~and~~ R2, and R3 one turn each.
b. Open V5, V12-V13, V16, V18. DO NOT open V6-V9.
c. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ **V12** V13 **V14 V15** V16 **V17** V18 **V19**
d. Turn on the backing pump and convectron gauge controller
e. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller. Open V3.
f. When the cold cathode gauge reads < 5e-5 torr, open V17 and turn on the RGA.
g. If the system pressure and RGA scan are acceptable, turn off the RGA.
h. Close V3, V13, V16 and V17. Back off R1 and R2.
i. Turn off pumps and controllers.
j. **V1 V2 V3** V5 **V6 V7 V8 V9 V10** V12 **V13 V14 V15 V16 V17 V18 V19**
k. Proceed to step 3.

3. Argon purge

a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~V12 **V13 V14 V15 V16 V17 V18 V19**
b. Back off R1. Open V1.
c. Set R1 to 20psig.
d. Open V4.
e. Wait for P3 to read > 5 psi. Open V10 1/4 turn. Argon will bleed out the 5psig relief.
f. Wait 5 minutes, then close V10.
g. Start Pump1.
h. Once P3 reads 20psi, close V1 and V4. Back off R1.
i. Continue pumping for desired interval.
j. Turn off Pump1.
k. Open V10 to vent argon.
l. When P3 reads < 6psi, close V10, V12.
m. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10 V12 V13 V14 V15 V16 V17 V18 V19**
n. Proceed to step 4

4. Post-purge pump-down

a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ **V12 V13 V14 V15 V16 V17 V18 V19**
b. Check that P3 reads < 6psi. Open V10 to relieve pressure. Close V10 when done.
c. Open V4 and crank down R1 1 turn.
d. Start the backing pump and convectron gauge controller.
e. Slowly open V16.
f. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller.
g. When the cold cathode gauge reads < 5e-5 torr, open V17 and turn on the RGA.
h. Close V4 and back off R1.
i. If the system pressure and RGA scan are acceptable, turn off the RGA, close V16 and V17.
j. Turn off pumps and controllers.
k. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** V11 **V12 V13 V14 V15 V16 V17 V18 V19**
l. If the partial pressures are not acceptable, repeat procedure from step 3.
m. If the Xenon reclamation cylinder is filled, proceed to step 6.

5. Xenon reclamation cylinder fill procedure

a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ **V12 V13 V14 V15 V16 V17 V18 V19**
b. Back off R2. Open V2 and V12.
c. Open V13, V14, and V18. Check that V10 is closed. Check that V5 is open.
d. Slowly set R2 to 200psig.
e. ~~Carefully open V4~~
~~f. Once P3 reads 200psig, close V4~~
g. Read the gas temperature at the TC. When T > 15 deg C, continue to next step.
h. Slowly set R2 to 300psig (225psig initial)
~~i. Open V4~~
j. Once P3 reads 300psig (225psig initial), close V2 and back off R2.
k. Chill C1 with LN until P4 bases out.
l. Close ~~V4 and~~ V14.
m. Open V2. Slowly set R2 to 50 psig.
~~n. Open V4~~ Check P5 is based out.
o. Once P3 reads 50 psig, close V2, ~~V4~~ and back off R2.
p. Open V14.
q. Continue to chill C1 with LN until P4 bases out.
r. Close V13 ~~and~~ ,V14 and V18. Stop chilling C1.
s. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**
t. Proceed to step 6.

6. Chamber fill from Xenon reclamation cylinder

a. **V1 V2 V3 V4** V5 **V6 V7 V8 V9 V10** V11 V12 **V13 V14 V15 V16 V17 V18 V19**
~~b. Close V11~~
b. Back off R3. Check that V18 is closed. Open V14.
c. If P5 < 300psig (225psig initial) at any point in step 6, turn on heat to C1.
d. Once P5 > 300psig (225psig initial), set R3 to 200psig(150psig initial); turn off C1 heat.
~~e. Close V4.~~
f. Open V13.
g. Open ~~V6, V8~~ V5.
h. When P3 reads 200psig, close V13.
i. Check the temperature at the TC. When T > 15 deg C, continue
j. Set R3 to 300psig (225psig initial).
k. Open V13.
l. When P3= 300psig (225psig initial), close V13 and V14.
m. ~~Close V5, V6, V8.~~ Back off R3.
n. TPC is ready to operate.
o. **V1 V2 V3 ~~V4~~ ~~V5~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**

7. TPC operation
a. **V1 V2 V3 ~~V4~~ ~~V5~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**
~~b. Open V6,V7 or V8,V9 and V11~~
d. Start pump1; set to desired flow rate
b. Open V6,V7 or V8,V9 ~~and V11~~ as needed to control flow and purification (usually close V5 but may be left open)
e. Monitor total flow with FM1. Adjust pump controller as required.
f. Log flow and pressure at P4, if desired.
g. **V1 V2 V3 ~~V4~~ V5** V6 V7 **V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19** (V8,V9 may be open instead of V6,V7)

8. TPC shutdown
a. **V1 V2 V3 ~~V4~~ V5** V6 V7 **V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**(V8,V9 may be open instead of V6,V7)
b. Stop pump1
c. Close V6-V9, ~~as required..~~Open V5.
d. Stop data logger.
e. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**

9. Cryogenic Xenon reclamation from TPC
a. **V1 V2 V3 ~~V4~~ ~~V5~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **V13 V14 V15 V16 V17 V18 V19**
b. Open ~~V5,~~ V13, V14, V18. ~~Close V12.~~ Check V5 and V12 are open. Check R3 is fully backed off.
c. Chill C1 with LN.
d. Once P4 bases out, operate Pump1 (to rattle piston valves, hopefully releasing gas trapped between Pump1 and CV1); check for pressure spike; allow to base out. ~~Close V13.~~
e. Close V13, V14, V18.
f. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **~~V12~~ V13 V14 V15 V16 V17 V18 V19**

10. Let-up TPC to Argon
a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10** ~~V11~~ V12 **~~V12~~ V13 V14 V15 V16 V17 V18 V19**
b. Back off R1. Open V1.
c. ~~Set~~ Slowly open R1 to ~~15~~ 2 psig.
~~c. Open V4.~~
d. When P3 > ~~0~~ 2 psig, close V1. Back off R1 until desired purge gas flow is achieved.
f. Open V10. Leave open during service
~~g. Once the 5 1/3 psi relief is closed, close V10, V11~~
h. Proceed with service or disassembly of TPC. When removing lid, leave 1 main flange bolt loosely in place until lid is fully separated from vessel, and any residual pressure is vented.
i. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 ~~V10~~** V10 **~~V11~~ V12 V13 V14 V15 V16 V17 V18 V19**

11. Replacement of Argon gas supply cylinder
a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10 ~~V11~~ V12 V13 V14 V15 V16 V17 V18 V19**
b. Make certain V1 is closed. Back off R1.
c. Disconnect R1 from Ar cylinder.
d. Connect new Ar cylinder to R1.
e. Crank down R1 1 turn.
f. Open V3.
g. Start backing pump and convectron gauge.
h. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller.
g. When the cold cathode gauge reads < 5e-5 torr, close V3 and turn off pumps.
h. Back off R1.
i. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10 ~~V11~~ V12 V13 V14 V15 V16 V17 V18 V19**

12. Replacement of Xenon gas supply cylinder
a. **V1 V2 V3 ~~V4~~** V5 **V6 V7 V8 V9 V10 ~~V11~~ V12 V13 V14 V15 V16 V17 V18 V19**
b. Make certain V2 is closed. Back off R2.

b. Make certain V2 is closed. Back off R2.
c. Disconnect R2 from Xe cylinder.
d. Connect new Xe cylinder to R1.
e. Crank down R2 1 turn.
f. Open V3
g. Start backing pump and convectron gauge
h. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller.
g. When the cold cathode gauge reads < 5e-5 torr, close V3 and turn off pumps.
h. Back off R2.
i. **V1 V2 V3 V4** V5 **V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17 V18 V19**

13. Reclamation of Xenon back into Xenon gas supply cylinder (at end of experiment, or to repair or reconfigure reclamation gas subsystem; assume entire system is filled with Xe and reclamation cyl. C1 is not isolatable)
a. **V1 V2 V3** V5 **V6 V7 V8 V9 V10** V12 **V13 V14 V15 V16 V17 V18 V19**
b. Back off R2. Open V2. Check that V5 and V12 are open.
c. Chill Xe supply cyl. with LN until P3, P4 and R2 high side bases out. Maintain LN temp.
d. Open V13, V18 , and V14. Wait until P3, P4 and R2 high side base out. Maintain LN temp.
e. Start Pump1 (to rattle piston valves, hopefully releasing gas trapped between Pump1 and CV1).
f. Close V2, V5, V12, V13, V18, V14. Plug high side of R2.
g. Back off and disconnect R2 from Xe cylinder.
h. **V1 V3 V5 V6 V7 V8 V9 V10 V12 V13 V14 V15 V16 V17 V18 V19**

Relief Valve Capacity

There are no operating conditions whereby a sudden pressure rise can occur, such as a sudden release of energy leading to rapid gas heating, or loss of insulating vacuum. We consider some extraordinary circumstances:

Pressure Rise under Gas Cylinder Regulator Failure

This is probably the most credible mechanism for accidental overpressure (someone accidently screws a regulator all the way in, then opens a valve downstream) Regulators are Matheson Dual Stage High Purity Stainless Steel, model 3810 :

maximum flow rate (@2500 psi N2 inlet pressure)

$Q_{reg} := 300SCFH \qquad Q_{reg} = 5\,SCFM$

Pressure Relief valve is a Swagelok R4. From relief valve catalog ms-01-141.pdf, flow curves are:

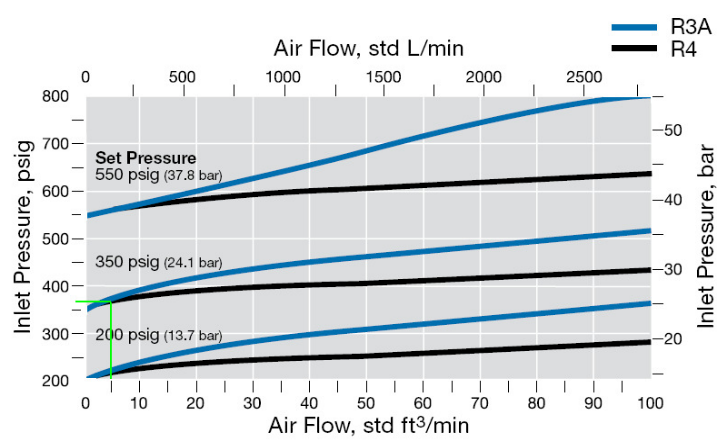


Fig 16. Pressure Relief Pressure Drop

For a set pressure of 350 psig, and a flow rate Q_{reg}, we find (green lines) an inlet pressure of:

$P_{inlet} := 370psi$ ASME Boiler and Pressure Vessel Code, Section VIII subsection UG-125 Overpressure Protection subsection (c) calls for (in this case) a maximum of 10% vessel overpressure under relief condition.

$\frac{P_{inlet}}{350psi} - 1 = 5.7\%$ OK

TPC Gas System parts list

1			TPC Gas System parts list			
2						Pressure
3	ID	MFR.	Part Number	Cle	Note/Product Description	rating (psig)
4		Swagelok				
5	V3,V4,V10,V11,V17		SS-8BG-V47-VD		1/2" valve Female VCR	1000
6	" (mixed)		SS-8BG-VCR-VD		1/2" valve Male VCR	1000
7			SS-R4M8F8-SC11		Relief valve .25 orifice	6000
8			SS-4R3A5		Relief valve .14 orifice	6000
9			177-R3A-K1-A		350-750 psi spring kit for line 6	-
10			177-R3A-K1-A		0-350 psi spring kit for line 6	-
11			177-13K-R4-A		0-350 psi spring kit for line 5	-
12			SS-FM4RM4RF4-12		1/4" VCR hose M/F fittings 12" lg	3100
13			SS-4-VCR-7-8VCRF-SC11		1/2" to 1/4" VCR reducing adapter	14300
14			SS-8-WVCR-6-DF-SC11		1/2" VCR close coupling	5800
15			SS-8-VCR-T-SC11		1/2" VCR Tee	10900
16			Ni--8-VCR-2-SC11	-	1/2" Ag plated Ni VCR gasket	-
17			Ni-4-VCR-2-SC11	-	1/4" Ag plated Ni VCR gasket	-
18			SS-8-VCR-CP-SC11		1/2" VCR cap	-
19			SS-8-VCR-P-SC11		1/2" VCR plug	-
20			SS-8-VCR-9-SC11		1/2" VCR elbow	10900
21			SS-4-VCR-2-4-SC11		1/4" VCR elbow	14300
22	Filter		SS-6TF2-15-SC11		15 micron TF type filter 3/8 MPT	3000
23			SS-8-VCR-7-6-SC11		3/8 NPT to 1/2" VCR female connector	5300
24			SS-8-VCR-7-8-SC11		1/2 NPT to 1/2" VCR female connector	4900
25			SS-4-VCR-1-4-SC11		1/4 NPT to 1/4" VCR male connector	8000
26			SS-8-VCR-4-SC11		1/2" VCR Male tube nut	-
27			SS-8-VCR-1-SC11		1/2" VCR female tube nut	-
28			SS-4-VCR-4-SC11		1/4" VCR Male tube nut	-
29			SS-4-VCR-1-SC11		1/4" VCR female tube nut	-
30			SS-8-VCR-3-SC11		1/2" VCR socket weld	3000
31			SS-6-VCR-3-SC11		1/2" VCR socket weld 3/8 tube	8200
32			SS-FM4RF4RF4-36		1/4" VCR hose F fittings 36" lg	3100
33			SS-FM4RM4RF4-48		1/4" VCR hose M/F fittings 48" lg	3100
34			SS-FM4RF4RF4-24H		1/4" VCR hose F fittings 24" lg	3100
35			SS-6-RB-4-SC11		3/8 NPT to 1/4 NPT reducing bushing	3000
36			6LV-8-VCR-3S-4TB7		1/2 VCR to 1/4" tube reducing gland	5100
37			-		3/8 OD x .035W 316SST Tubing	2936
38			-		1/4 OD x .035W 316SST Tubing	4375
39			SS-8-VCR-CS		1/2" VCR cross	10900
40			SS-4-WVCR-1-4		1/4 NPT male to 1/4 VCR female	10200
41			SS-4-VCR-T		1/4" VCR tee	14300
42			SS-4-VCR-CS		1/4" VCR cross	14300
43	V13-V15,V18		SS-DSV51		1/4" VCR diaphragm valve	2500
44			SS-4-WVCR-7-4		1/4" fem VCR to 1/4 fem NPT	6600
45			SS-8-VCR-3-4TSW		1/2 VCR to 1/4" tube reducing gland	13600
46			SS-4-VCR-3		1/4 VCR socket weld gland	5500
47			SS-8-VCR-6-DM-4		Double male VCR reducing union 1/2 to 1/4	10900
48			SS-4-VCR-7-4		1/4 male VCR to 1/4" NPT female	6600
49			SS-4-VCR-1-00032		1/4 male VCR to 9/16-18 adapter	14300
50			SS-8-VCR-1-01081		1/2 male VCR to 9/16-18 adapter	15000
51			SS-4-VCR-3-4TA		1/4 swage to 1/4 VCR gland	10200
52		McMaster-Carr				
53	P1,P2		4066K418		0-600 psig dry gauge	600
54	P3		4005K48		0-400 psig dry gauge	400
55	P5		3852K24		0-2000 psig dry gauge	2000
56		Acme Cryogenics (for LLNL orig.)				
57	C1		C1		Xenon condensation cylinder	3000
58		Pump Works Inc.				
59	P1		PW2070		Positive displacement pump	1400

60		SAES Pure Gas inc.			
61			HP190	inert gas purifier	1000
62			MC50	inert gas purifier	1000
63	V5-V9			valves supplied w/ above purifiers	1000
64		Carten			
65	V16		HF2000	2" straight thru valve	350
66		Matheson			
67	R1-R3		3818-580	15-350 psi regulator with G type inlet	3500
68		Omega			
69	FM1, FM2		FMA1818	flowmeter 5slpm	500
70	P		MMG500V10P3C0T3A6	500 psig pressure transducer	500
71	TC		EI1202105/TC-K-NPT-U-72/3"	Pipe plug TC probe	2500
72		Ceramtec			
73			18088-01-CF	SHV-20 Coaxial feedthrough, 1.33" CF flange	250
74			8880-02-CF	SHV-5 Coaxial Feedthrough, 1.33" CF flange	1400
75			18898-01-CF	Multipin feedthrough 2.75" CF flange, 32 pin	375

9. Test Procedures

9.1 Pressure Vessel and 350 MOP Head

These components have been tested at LLNL to higher pressures than used here. No retesting is needed, as there are no corrosive gasses or other materials used, and the vessel and lid have not been modified. Any minor modifications, such as rewelding a VCR fitting to the Vessel will require a retest. MESN-99-020-OA does not specify any retesting requirement. Since no cryogens are used, the vessel and head may be retested using a hydrostatic test in accordance with ASME Boiler and Pressure Vessel Code Section VIII, subsection UG-99 Standard Hydrostatic Test. Test pressure is 1.5x MAWP= 525 psig. Nevertheless, this component will be further tested, in its installed configuration, along with the gas system test at a test pressure of 1.25x MAWP = 438psig (313 initial).

9.2 Spool

This component will be hydrostatically tested by the manufacturer in accordance with ASME Boiler and Pressure Vessel Code Section VIII, subsection UG-99 Standard Hydrostatic Test, and tagged by the manufacturer, and may be used as received. Nevertheless, this component will be further tested, in its installed configuration, along with the gas system test at a test pressure of 1.25x MAWP = 438psig (313 initial).

9.3 Octagon

This component is not rated for pressure by the manufacturer, though the manufacturer does supply pressure rating recommendations. It shall be tested by either a certified pressure installer here at LBNL, or by an independent testing lab. It shall be tested using a hydrostatic test in accordance with ASME Boiler and Pressure Vessel Code Section VIII, subsection UG-99 Standard Hydrostatic Test. Test pressure is 1.5x MAWP= 525 psig. Nevertheless, this component will be further tested, in its installed configuration, along with the gas system test at a test pressure of 1.25x MAWP = 438psig (313 initial).

9.4 Source Insertion Tube

This component will be hydrostatically tested by the manufacturer in accordance with ASME Boiler and Pressure Vessel Code Section VIII, subsection UG-99 Standard Hydrostatic Test, and tagged by the manufacturer, and may be used as received. Nevertheless, this component will be further tested, in its installed configuration, along with the gas system test at a test pressure of 1.25x MAWP = 438psig (313 initial).

9.5 Gas system

All other attachments, fittings and components are pressure rated by the manufacturer as in the above table and may be used as installed up to MAWP. Nevertheless, this system will be tested, in its installed configuration, along with the gas system test at a test pressure of 1.25x MAWP = 438psig (313 initial), as described below:

9.6 Final assembled system pressure check

Completed gas system, including pressure vessel, shall be pneumatically tested to 125% MAWP in place using a remote test system comprising a gas cyl., regulator, gauge, test valve, and vent valve. There are three sections of the complete gas system having different MAWP's; therefore the test is in three parts. Test pressures for the 3 sections are (125%MAWP):

a. 438 psig (313 initial) for the pressure vessel (MAWP=350 psig/250 psig initially) ,
b. 563 psig for the gas purifier and supply section (MAWP=450 psig), and
c. 1875 psig for the cryogenic reclamation section (MAWP=1500 psig).

The test shall be repeated for each section that is modified. The test system and operator shall be located a minimum of 8 ft. from the main pressure vessel, with no line of sight to system (behind a barrier; this can be a room wall or the existing wall of cabinets and workbenches presently in 70A-2263). Testing is to be performed by a Certified Pressure Installer, and witnessed by the M.E. Dept. Designee for Pressure Safety, at a minimum. Note that there is no V4 or V11 ; these valves were present in an earlier draft configuration and have been removed. Valves have not been renumbered to avoid confusion.

Prepare for test as follows (initial each step)**:**

1. Procure:

a. Two full gas cylinders, size 200 SCFM or more of clean Ar, N2, CO2, or dry air with supply pressure 2200 psig min.

b. Calibrated test gauge(s) for reading 438 psig (313 initial), 563 psig, and 1875 psig to within 3% accuracy. Gauge maximum scale pressure should not be less that 1.2x or more than 4x the test pressure. Electronic gauges (calibrated) are permissible, and are not subject to the above range limitations.

c. Regulator(s), to provide above pressures in (b) to fit cyl. in (a).

d. 30-35 ft. long high pressure clean gas service (e.g. McMaster P/N 5665K34 2-3 ea) or PTFE lined high pressure chemical hose (e.g McMaster P/N 5830K21, or similar), 2000 psig rated (min.), and fittings to connect to gas system at T1, T3.

e. Pressure relief valves that fit exhaust ports of existing relief valves set to a minimum of 5% over test pressure (1.05x T.P. = 460 psig (329 initial), 591 psig, and 1968 psig), to fit exhaust ports of 350 psig (250 initial), 450 psig, and 1500 psig relief valves. These pressure relief valves should not be set higher than 33% of test pressure. See step 3 below for explanation.

f. Test pressure isolation valve, and fill vent valve, rated for test gas maximum pressure.

g. Test pressure release vent valve on Tee, both rated for test gas maximum pressure.

2. Assemble remote gas cylinder, regulator(RT), test gauge(GT) for 1875 psig test pressure, test isolation valve(TV), vent valve(VV), and fill vent valve (VF) as shown in fig. 17 below, and locate around corner from experiment, out of line sight, and behind wall of cabinets, or wall. Note that the pressure relief valve shown in fig. 17 is optional (see step 3 below for more explanation), since test feed ports T1 and T3 cannot be isolated from the system pressure relief valves.

3. Install 460 psig (329 initial), 591 psig, and 1968 psig relief valves into exhaust ports of 350 psig (250initial), 450 psig, and 1500 psig relief valves, respectively. Note that this is permissible only because the system pressure relief vaves used, (Swagelok R3, R4 high pressure) are designed to be insensitive to back pressure; other types of pressure relief valves can be sensitive to back pressure and must be plugged while a separate test pressure relief valve installed as shown on fig. 17 (not optional).

4. Survey for, and remove any hazardous material (such as radioactive sources, flammable liquids, glassware, etc.) from line of sight to test area. Also remove as many other valuable or potentially hazardous materials such as glassware, dewars, electronic equipment as practical. Have fire extinguishers on hand.

5. Check that gas system is fully depressurized. Open V4 if closed, to connect T1 with P2 and open V14 and V18 if closed, to read pressure all the way to V13.

6. Barricade test area to prevent personnel ingress, notify building manager of impending test. Clear area of all people except for pressure test operator and witness(es).

Test 1500 psig MAWP subsystem (first) as follows (can be skipped if not needed for section retest):

7. Close V13, V15, if open. Open V14, V18 if closed. Screw in handle of R3 all the way. Check that C1 is fully depressurized.

8. Unplug T3 and install test hose. Open VT, screw in RT handle; keep VV, test gas cyl valve closed.

9. Start the backing pump and convectron gauge controller, Slowly open V15. When the convectron gauge reads < 1e-2 torr, close V15, and turn off backing pump and convectron gauge controller. Close V15.

10. Close V18. Back off R3 handle fully. Check that V14 is open. Check that V13 is closed. Leave V15 closed.

11. Back off RT handle fully.

12. Open test gas cyl. valve 1-2 turns.

13. Screw in RT handle slowly, in steps in steps of 33% MAWP (500 psi), each time closing VT, and watching GT to see that stable pressures are achieved. Watch GT for 5 minutes minimum, each time. If leaks occur, back off pressure to 300 psig (20% MAWP) max. and inspect to find leak. See note on possible methods below fig. 17. Once found, back off RT fully, open VV to depressurize fully, and fix leak. If no leaks occur, continue increasing pressure (stepwise, as above) until 1500 psig reads on test gauge. Watch GT closely while increasing pressure to note when 1500 psig relief valves open; pressure should drop slightly for each one. If this is not observed, 1500 psig relief valve(s) may be leaking, or not opening properly, and step 15 below must be performed. Record pressures on system gauges. Increase pressure to 1875 psig. Hold for 5 minutes, if stable then back off RT, close test gas cyl. valve and release system pressure; otherwise depressurize and fix leak as above.

14. Remove 1968 psig relief valves from exhaust ports of 1500 psig relief valves.

15.(not necessary if both P.R valve openings observed in step 13). Close VV, and progressively repressurize system until relief valve exhausts, but not past 1600 psig. Depressurize and vent pressure. Adjust 1500 psig relief valve if needed and repeat this step.

16. Remove hose from T3, replace plug. Proceed to purge system as described in Gas System Operation.

<u>Test 450 psig MAWP subsystem (next) as follows (skip steps 22-27 if not needed for section retest):</u>

17. Check that entire system is depressurized.

18. Close valves V1-V9, V12, V15, V16, V17. Back off R1, R2.

19. Remove T1 plug and install hose end.

20. Start the backing pump and convectron gauge controller, Slowly open V3. When the convectron gauge reads < 1e-2 torr, close V3, and turn off backing pump and convectron gauge controller.

21. Check that installed test gauge, GT, and regulator, RT, are for 563 psig test pressure.

22. Open valves V6, V8 Check that valves V3, V5, V7,V9, V12, V15, V16, V17 are closed.

23. Back off RT handle fully.

24. Open test gas cyl. valve 1-2 turns.

25. Screw in RT handle slowly, in steps of 33% MAWP (150 psi), each time closing VT, and watching GT to see that stable pressures are achieved. Watch GT for 5 minutes minimum, each time. If leaks occur, back off pressure to 90 psig (20% MAWP) max. and inspect to find leak. See note on possible methods below fig. 17. Once found, back off RT fully, open test vent valve VV to depressurize fully, and fix leak. If no leaks occur, continue increasing pressure (stepwise, as above) until 450 psi reads on GT. Watch GT closely while increasing pressure to note when 450 psig relief valve opens; pressure should drop slightly. If this is not observed, 450 psig relief valve may be leaking, or not opening properly, and step 27 below must be performed. Record pressures on system gauges. Increase pressure to 563 psig. Hold for 5 minutes, if pressure is stable, then back off regulator fully, close test gas cyl. valve, and release system pressure through VV; otherwise depressurize and fix leak as above.

26. Remove 591 psig relief valve from exhaust port of 450 psig relief valve.

27. (not necessary if P.R valve opening observed in step 25). Close VV, and progressively repressurize system until 450 psig relief valve exhausts, but not past 475 psig. Depressurize and vent pressure. Adjust relief valve if needed then repeat this step.

<u>Test main pressure vessel (directly following 450 psig MAWP subsystem) as follows:</u>

28. Open valves V5, V12, V13. Close valves V6, V8, V10, V14, V15, V18. Leave valves V3, V16, V17 closed. Back off R3 handle fully.

29. Back off RT handle fully.

30. Open test gas cyl. valve 1-2 turns.

31. Screw in test regulator slowly, in steps of 33% MAWP (115 psi, 85 psi initial), each time closing VT, and watching GT, to see that stable pressures are achieved. Watch GT for 5 minutes minimum, each time. If leaks occur, back off pressure to 50 psig (20% MAWP) max. and inspect to find leak. See note on possible methods below fig. 17. Once found, back off RT fully, open VV to depressurize fully, and fix leak. If no leaks occur, continue increasing pressure (stepwise, as above) until 350 psig (250 initial) reads on GT. Watch GT closely while increasing pressure to note when 350 (250 initial) psig relief valves open; pressure should drop slightly for each one. If this is not observed, 350 psig (250 initial) relief valve(s) may be leaking or not opening properly, and steps 33-35 below must be performed. Record pressures on system gauges. If gas system pressure gauge (P3) cannot read higher than 438 (313 initial) psi, then hold for 5 minutes, then back off regulator, close test gas cyl. valve, and release system pressure. Remove P3, plug, and repressurize to 438 psig (313 initial) as above. Hold for 5 minutes, if stable, then back off regulator, close test gas cyl. valve and release system pressure; otherwise depressurize and fix leak as above. Replace P3, if removed.

32. Remove 460 psig (329 initial) psig relief valve from exhaust port of 350 (250 initial) psig relief valve located between V13 and V15.

33. (not necessary if both P.R valve openings observed in step 31). Close VV, and progressively repressurize system until 350 (250 initial) psig relief valve located between V13 and V15 exhausts, but not past 380 (275 initial) psig. Depressurize and vent pressure. Adjust relief valve if needed and repeat test.

34. Close V13, and remove 460 psig (329 initial) psig relief valve from exhaust port of 350 (250 initial) psig relief valve located on main pressure vessel.

35.Close VV, and progressively repressurize system until 350 (250 initial) psig relief valve located on main pressure vessel exhausts, but not past 380 (275 initial) psig. Depressurize and vent pressure. Adjust relief valve if needed and repeat test.

36. Remove hose from T1, replace plug.

37. Start the backing pump and convectron gauge controller, Slowly open V3. When the convectron gauge reads < 1e-2 torr, close V3, and turn off backing pump and convectron gauge controller. Close V3.

38. Attach pressure test tags to pressure relief valves. These are found in Appendix D of PUB3000. File pressure test report (also in Appendix D) with Regulator Shop.

Leak checking may be performed at full MAWP after successful pressure testing. No tightening of flange bolts or other repair is allowable when under pressure.

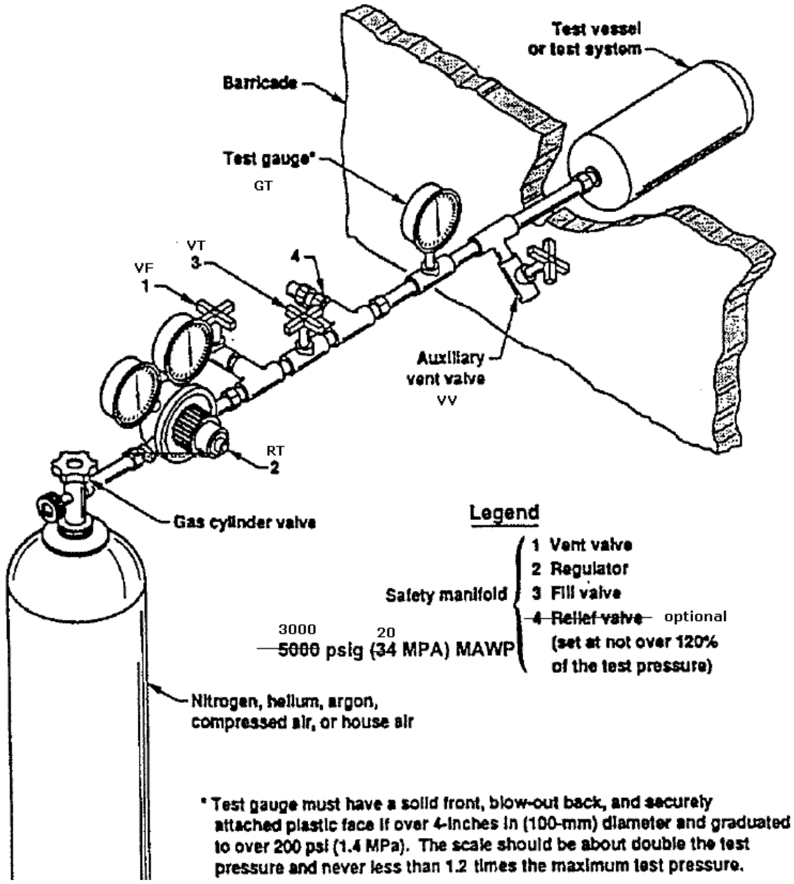


Fig. 17 Pressure Test Set up (Pneumatic, in-situ)

Leak Detection Methods for Pressure Leaks (not Vacuum):

Leak checking may be performed at full MAWP after successful pressure testing. Prior to pressure testing. leak checking may be performed up 20% MAWP

Methods (not conclusive):

1. SNOOP - this is essentially soapy water; - NOT PREFERABLE, as it may be pulled into vacuum. If used, clean area throughly with DI water afterwards before pulling vacuum.

2. Helium Leak Testing (sniffer) - DO NOT USE, glass in PMT's are very permeable to He, which will then ruin them.

3. Hydrogen Leak Testing (sniffer) - PREFERABLE, uses 5% H2/95% N2 nonflammable mix test gas. Sniff as with He using appropriate equipment.

4. Gas Bag - PREFERABLE, Wrap plastic bag material very loosely around suspect joint and seal tightly; watch for inflation.

5. LACO Technologies Gas Check 3000 (P/N LHHLD-G3), leak detector - PREFERABLE, which can sniff for a variety of different gasses based on differential thermal conductivity (to air).

10. Appendix

to be added->Pressure Test Reports for Vac. Valve, Spool, Octagon, Source Tube, Gas System